THE UNIVERSITY of TULSA

McDougall School of Petroleum Engineering

Fluid Flow Projects

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

May 12, 2011

Tulsa University Fluid Flow Projects
Seventy Sixth Semi-Annual Advisory Board Meeting Agenda
Thursday, May 12, 2011

Wednesday, May 11, 2011

Tulsa University High-Viscosity Oil Projects
Advisory Board Meeting
University of Tulsa – H. A. Chapman Stadium - OneOK Club
3112 East 8th Street
Tulsa, Oklahoma
8:15 a.m. – Noon

Tulsa University High-Viscosity Oil Projects and Tulsa University Fluid Flow Projects
Workshop Luncheon
University of Tulsa – H. A. Chapman Stadium - OneOK Club
3112 East 8th Street
Tulsa, Oklahoma
12:00 – 1:00 p.m.

Tulsa University Fluid Flow Projects Workshop
University of Tulsa – H. A. Chapman Stadium - OneOK Club
3112 East 8th Street
Tulsa, Oklahoma
1:00 – 3:00 p.m.

Tulsa University High-Viscosity Oil Projects, Tulsa University Fluid Flow Projects and
Tulsa University Paraffin Deposition 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 and Tulsa University Fluid Flow Projects
Reception
University of Tulsa – H. A. Chapman Stadium - OneOK Club
3112 East 8th Street
Tulsa, Oklahoma
6:00 – 9:00 p.m.

Thursday, May 12, 2011

Tulsa University Fluid Flow Projects
Advisory Board Meeting
University of Tulsa – H. A. Chapman Stadium - OneOK Club
3112 East 8th Street
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 – H. A. Chapman Stadium - OneOK Club
3112 East 8th Street
Tulsa, Oklahoma
5:30 – 9:00 p.m.

Friday, May 13, 2011

Tulsa University Paraffin Deposition Projects
Advisory Board Meeting
University of Tulsa – H. A. Chapman Stadium - OneOK Club
3112 East 8th Street
Tulsa, Oklahoma
8:00 a.m. – 1:00 p.m.

Tulsa University Fluid Flow Projects
Seventy Sixth Semi-Annual Advisory Board Meeting Agenda
Thursday, May 12, 2011

8:00 a.m.	**Breakfast – Allen Chapman Activity Center – Chouteau**		
8:30	**Introductory Remarks**		Cem Sarica
8:45	**TUFFP Progress Reports**		
		High Pressure - Large Diameter Multiphase Flow Loop	Scott Graham/ Cem Sarica
		Effects of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes	Ceyda Kora
10:15	**Coffee Break**		
10:30	**TUFFP Progress Reports**		
		Wave Characteristics in Annular Gas-Liquid Flow	Abdel Alsarkhi
		Liquid Entrainment in Annular Two-Phase Flow in Inclined Pipes	Abdel Alsarkhi
		A Unified Drift Velocity for Intermittent Flow	Ben Jeyachandra
11:45 a.m.	**Lunch – Allen Chapman Activity Center - Gallery**		
1:00 p.m.	**TUFFP Progress Reports**		
		High Oil Viscosity Two-Phase Flow in Inclined Pipes	Ben Jeyachandra
		Investigation of Slug Length for High Viscosity Oil-Gas Flow	Eissa Alsafran
2:30	**Coffee Break**		
2:45	**TUFFP Progress Reports**		
		Low Liquid Loading Three-Phase Flow	Kiran Gawas
		Transient Gas/Liquid Two-Phase Modeling	Michelle Li
		Liquid Unloading from Gas Wells	Ge (Max) Yuan
4:15	**TUFFP Business Report**		Cem Sarica
4:30	**Open Discussion**		Cem Sarica
5:00	**Adjourn**		
5:30	**TUFFP/TUPDP Reception - Allen Chapman Activity Center - Atrium**		

Table of Contents

TUFFP Business Report

Appendices

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 downward inclination tests were completed and the data were analyzed and compared with horizontal data acquired by Gokcal (2005 and 2008) and Kora (2010). The facility is readied for the upward flow experiments. The testing will resume shortly after the Advisory Board meeting. This study is expected to be completed by August 2011.

  2. *Slug Length Study:* Dr. Eissa Al-Safran of Kuwait University continues to investigate the slug length for high viscosity oils. A new empirical model which is function of the dimensionless inverse viscosity number is developed, and performance is compared with the other slug length models.

  3. *Medium Viscosity Oil Study:* Only few experimental studies for medium oil viscosity (20cP<μ_O<200cP) 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, there is a need to verify existing mechanistic models for medium liquid viscosities. If needed, new closure relationships or models will be developed.

     Experimental studies will be started right after the completion of upward flow testing of the current study.

- *"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 construction of the facility is complete. Commissioning of the gas compressor will take place in June 2011 with shakedown tests of the entire facility beginning in July 2011.

  The first TUFFP study to be conducted utilizing the new facility is "Effect of Pressure on Liquid Loading". Currently, efforts are focused on identifying and acquiring the proper instrumentation to characterize the flow.

- *"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 Advisory Board meeting, the 6 in. facility has been inclined 2° from horizontal; a new compressor dedicated to this project has recently been purchased; a new film extraction device is designed and being manufactured to be used in entrainment fraction measurements along with Iso-kinetic Probe and visualization through High Speed Camera; and modeling study is continued and a frame work for the model is developed.

- *"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 rate and coalescence rate. Understanding the basic physics of these phenomena 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, is conducting this project. 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, the efforts are now diverted to development of a new model based on the drift flux approach for all flow patterns. During this period, a simplified isothermal drift flux model has been developed as a preliminary model. Simulator design, code and validation are ongoing.

- *"Liquid Unloading from 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 will be observed and measured along the pipe for various deviation angles. The effects of well deviation to the liquid loading will be investigated. The Turner model and its modified versions along with other models (including the TUFFP unified model) will be evaluated with experimental results. The available models will be improved or a new model developed based on the experimental measurements and observations.

  Design of the experimental facility was completed. The facility modifications are near completion. The experimental campaign will ensue.

- "*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 increases to 16 (15 industrial companies and BOEMRE). Efforts continue to further increase the TUFFP membership level. A detailed financial report is provided in this report. The sum of the 2011 income, facility utilization and the reserve account is projected to be $910,240.00. The expenses for the industrial member account are estimated to be $810,527.78 leaving a positive balance of $99,711.96.

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 a budget of $540,000/year. Tulsa University High Viscosity Oil Projects (TUHOP) Joint Industry Projects is into its third year. TUHOP currently has currently five members with recent addition of PetroChina.

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 equivalent of one year TUFFP membership fee will be paid to TUFFP. Current industrial members of the JIP are Chevron, ConocoPhillips, Marathon, Shell, Nalco and Multichem. Nalco and Multichem will each pay $30,000 facility utilization fee.

Fluid Flow Projects

76^{th} Fluid Flow Projects Advisory Board Meeting

Welcome

Advisory Board Meeting, May 12, 2011

Safety Moment

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

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Introductory Remarks

- 76th 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 (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
  - Kiran Gawas (Ph.D.) – India
  - Benin (Ben) Chelinsky Jeyachandra (MS) – India
  - Ge Yuan (MS) – PRC
  - Rosmer Brito (MS) – Venezuela
  - Mujgan Guner (Ph.D.) – Turkey
  - Wei Zheng (MS) – PRC
  - Feras Al-Ruhaimani (Ph.D.) – Kuwait

Team …

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

Guests

- Michael Malvick, Alyeska Pipeline Service Company
- Madhusuden Agrawal, ANSYS, Inc.
- Duraivelan Dakshinamoorthy – ANSYS, Inc.
- Jep Bracey, BHP
- Dr. Uwe Hampel, Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

Membership and Financial Status

- 16 Members in 2011
- Seoul National University Collaboration
  - Three Years Agreement with Possible Two Year Extension
  - TUFFP
    - Provides Guidance to Research Scholars (SNU Ph.D. Candidates) and Access to Facilities Through TUFFP Projects
    - Receives $110,000/Year

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Agenda

- 8:30 Introductory Remarks
- 8:45 Progress Reports
  - Executive Summary
  - High Oil Viscosity Two-Phase Flow in Inclined Pipes
- 10:15 Coffee Break
- 10:30 Progress Reports
  - Gas/Liquid Two-Phase Flow Behavior for Medium Liquid Viscosities
  - Investigation of Slug Length for High Viscosity Oil-Gas Flow
  - Low Liquid Loading in Gas/Oil/Water Pipe Flow

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Agenda …

- 11:45 Lunch – H. A. Chapman Stadium - OneOK Club
- 1:00 Progress Reports
  - High Pressure Test Facility Construction Update
  - Effects of Pressure on Low Liquid Loading
  - Liquid Unloading from Gas Wells
- 2:30 Coffee Break

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Agenda …

- 2:45 Progress Reports
  - Simplified Transient Gas-Liquid Two-Phase Flow Modeling
  - Unified Heat Transfer Modeling of Gas/Oil/Water Pipe Flow
  - Questionnaire Results
  - MEG Project

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Agenda …

- 4:15 TUFFP Business Report
- 4:30 Open Discussion
- 5:00 Adjourn
- 5:30 TUFFP/TUPDP Reception - OneOK Club

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Other Activities

- May 11, 2011
  - TUHOP Meeting
  - TUFFP Workshop
    - Excellent Presentations
    - Beneficial for Everybody
  - Facility Tour
- May 13, 2011
  - TUPDP Meeting

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Fluid Flow Projects

Executive Summary
of Research Activities

Cem Sarica

Chevron TUFFP Progress Update, May 12, 2011

Current Projects

- High Viscosity Multiphase Flow
- Low Liquid Loading Flow
- Up-Scaling Studies
- Liquid Unloading from Gas Wells
- Transient Modeling
- Unified Model
- Droplet Homo-phase Studies
- Three-phase Flow Studies
- Energy Minimization Modeling

Fluid Flow Projects

Chevron TUFFP Progress Update, May 12, 2011

Future Project

- Effects of MEG on Multiphase Flow

Fluid Flow Projects

Chevron TUFFP Progress Update, May 12, 2011

High Viscosity Multiphase Flow

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

Fluid Flow Projects

Chevron TUFFP Progress Update, May 12, 2011

High Viscosity Multiphase Flow

- Past Studies …
  - Kora (2010)
    - Investigation of Slug Liquid Holdup for High Viscosity Oil and Gas Flow
      - 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
    - New Closure Relationship

High Viscosity Multiphase Flow …

- Current Studies
  - Inclination Angle Effect Investigation (Jeyachandra)
    - Progress
      - Data Acquisition and Analysis for Downward Flow (- 2°)
    - Near Future Activities
      - Data Acquisition and Analysis for Upward Inclined (+2°) (June 2011)
      - Evaluation (July 2011)
        - Pressure Drop Models (Unified, Xiao and OLGA)
        - Closure Relationships for Slugs Characteristics
      - Closure Relationship Development (August 2011)
      - Final Report (September 2011)

High Viscosity Multiphase Flow …

- Current Studies …
  - Slug Length (Al-Safran)
    - Progress
      - Developed a New Correlation
- New Study
  - Medium Viscosity Study (20 cp – 200 cp) (Brito)
    - Progress
      - Literature Review
      - Designed a New Mixing Tee
      - Developed Testing Program
    - Near Future Activity
      - Testing in Fall 2011

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 $\pm 2^\circ$ Inclination Angles from Horizontal
    - Objectives
      - Acquire Similar Data as in Horizontal Flow Study
      - Develop Improved Closure Relationships

Low Liquid Loading Flow …

- Progress
  - Completed Horizontal Testing
    - High Superficial Gas Velocity
    - Low Water Cut
  - High Speed Camera Application to Detect the Onset of Entrainment Fraction and Droplet Size Measurement
  - Design of Liquid Film Removal Device for 6 in. ID Pipe
  - Modeling Framework

Low Liquid Loading Flow …

- Future Work
  - Manufacturing of Film Removal Device May 2011
  - Data Acquisition November 2011
  - Data Analysis Feb. 2012
  - Model Evaluation and Development June 2012
  - Final Report August 2012

Up-Scaling Studies

- Significance
  - Better Design and Operation
- Objective
  - Testing and Improvement of Existing Models for Large Diameter and Relatively High Pressures
- Past Studies
  - Low Pressure and 6-in. ID Low Liquid Loading (Fan and Dong)
  - High Pressure 2-in. ID (Manabe, 2002)

Up-Scaling Studies …

- New High Pressure, Large Diameter Facility
  - Operational by May 2011
  - HAZOP
    - No Volunteers from Members
    - Need a Member to Step-up
    - Looking for a Third Party as Alternative Solution

Up-Scaling Studies …

- First Project
  - Investigation of Low Liquid Loading Flow of Two-phases in Large Diameter Horizontal and Inclined Flow at Elevated Pressures (Guner)
    - Progress
      - Evaluation of Available Instrumentation for Large Pipe Diameter and High Pressure
    - Near Future Activity
      - Finalizing of Instrumentation
      - Implementation
      - Testing and Data Acquisition

Liquid Unloading from 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
  - 3 in. ID Three-phase Facility is Modified
- Near Future Activity
  - Data Acquisition and Analysis
  - Model Evaluation and Development

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

Fluid Flow Projects Chevron TUFFP Progress Update, May 12, 2011

Transient Modeling …

- Current Study (Choi)
  - Li Developed a Model
    - Based on Two-Fluid and Drift Flux
    - Compared with TUFFP Transient Flow Data
    - Developed a Driver Code to Determine Which Model to Use
    - Resigned
  - Project is Re-Assigned to Jinho Choi of SNU (Visiting Scholar)

Fluid Flow Projects Chevron TUFFP Progress Update, May 12, 2011

Transient Modeling …

- Current Activities
  - Approach is Changed
    - Drift Flux is Chosen
  - Development of a Simplified Isothermal Drift Flux Transient Model
    - Simulator Structure Design
    - Preliminary Code (Explicit Solver)
- Future Work
  - Code Debugging
  - 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

Fluid Flow Projects — Chevron TUFFP Progress Update, May 12, 2011

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

Fluid Flow Projects — Chevron TUFFP Progress Update, May 12, 2011

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
    - Developed a Correlation for Highly Inclined Pipes (45° to 90°)
  - On hold
    - Will be Continued in Summer 2011 When Dr. Alsarkhi Returns

Three-phase Flow Studies

- Significance
  - Good Understanding of Gas-Oil Flow
  - Poor Understanding of Gas-Oil-Water Flow
- Objective
  - Development of Improved Prediction Models
- Past Studies
  - Oil-Water
    - Trallero (1994), Horizontal
    - Flores (1996), Vertical and Deviated
    - Alkaya (1999), Inclined

Three-phase Flow Studies …

- Past Studies …
  - Three-phase
    - Keskin (2007), Experimental Horizontal Three-phase Study
    - Zhang and Sarica (2005), Three-phase Mechanistic Model Development
    - Need to More Research on Oil-Water Flow
  - Oil-Water Studies with Emphasis on Droplets
    - Vielma (2006), Horizontal Flow
    - Atmaca (2007), Inclined Flow
    - Sharma (2009), Modeling Based on Minimum Energy Concept

Three-phase Flow Studies …

- Current Activity
  - Various Other Projects Contribute to This Project
    - Low Liquid Loading Three-phase Flow
    - Unified Model and Software 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
  - Analogous Case to Oil/Water Identified for Gas/Oil
    - Drag Reduction Phenomena in Self-Aeration in Two-Phase Stratified Pipe Flow
    - Energy Minimization is Applied to This Problem
    - Compare Results with Lunde and Nossen (2007) Experimental Data

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

Future Project – 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

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

Fluid Flow Projects

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

Benin Chelinsky Jeyachandra

Advisory Board Meeting, May 12, 2011

Outline

- Recommendation from Fall ABM 2010
- Objectives
- Introduction
- Experimental Program
- Flow Characteristics
- Conclusions
- Future Tasks

Recommendations from Fall ABM 2010

- Slug Liquid Holdup
- Utilize Ring Type and Wire Type Capacitance Sensor

Objectives

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

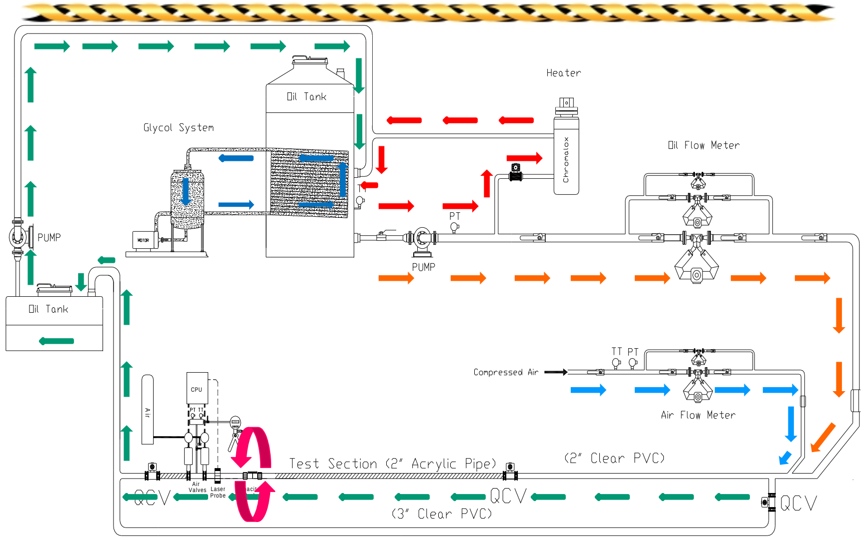
Introduction

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

Experimental Facility

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

Experimental Facility…



Fluid Flow Projects Advisory Board Meeting, May 12, 2011

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

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Two Phase Flow Characteristics

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

Instrumentation/Data Processing

- High Speed Camera
- Differential Pressure Transducer
- Laser Sensors
- Capacitance Sensors
- Quick Closing Valve
- DAQ Systems
- VBA Macros

Fluid Flow Projects

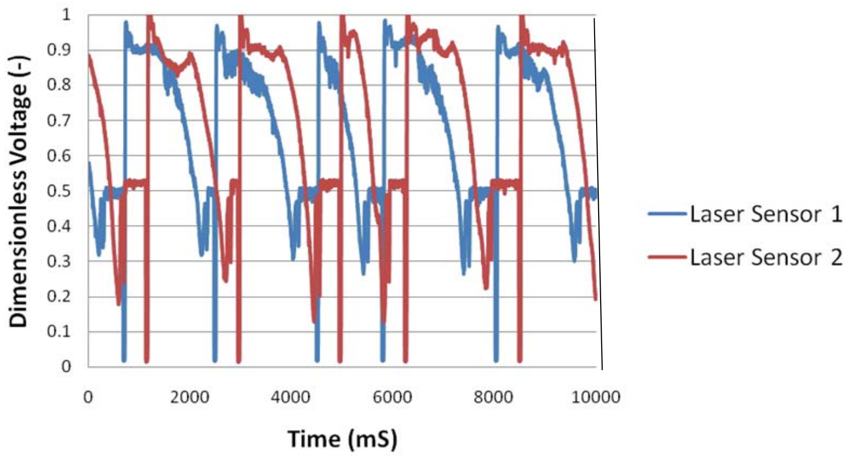
Experimental Study of Two Phase Flow Characteristics in -2° Inclined Pipe

Advisory Board Meeting, May 12, 2011

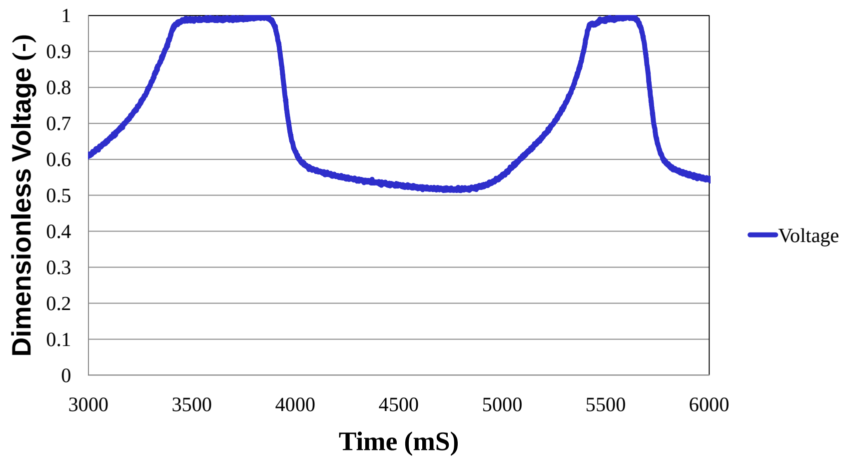
High Speed Video 1

High Speed Video 2

Laser Sensor Response
(585 cP v_{SL} - 0.1 m/s v_{SG} - 0.1 m/s)



Capacitance Sensor Response
(585 cP v_{SL} - 0.1 m/s v_{SG} - 0.1 m/s)



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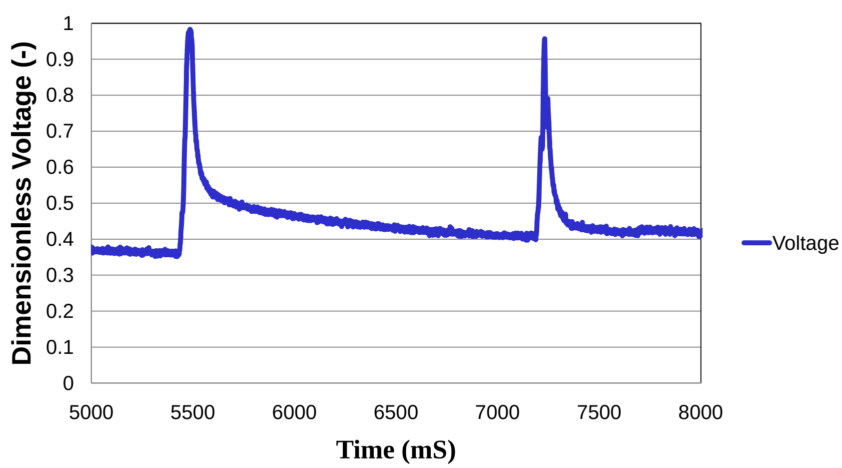
Capacitance Sensor Response…
(585 cP v_{SL} - 0.1 m/s v_{SG} - 2.5 m/s)



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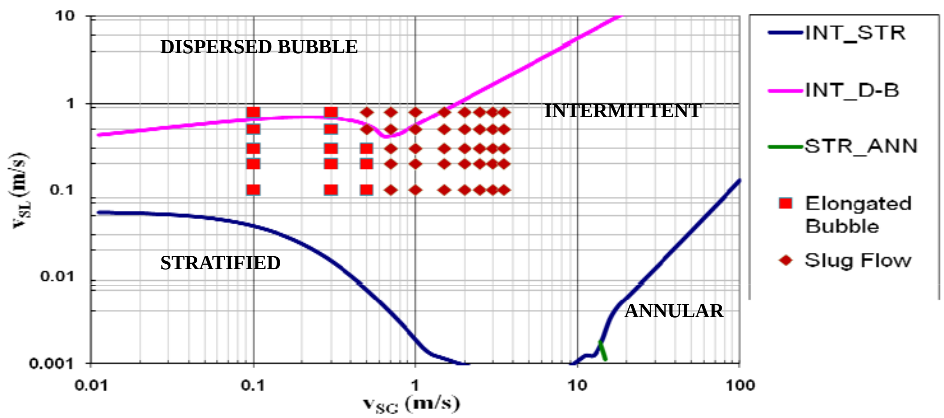
Unified Model Flow Pattern
585 cP



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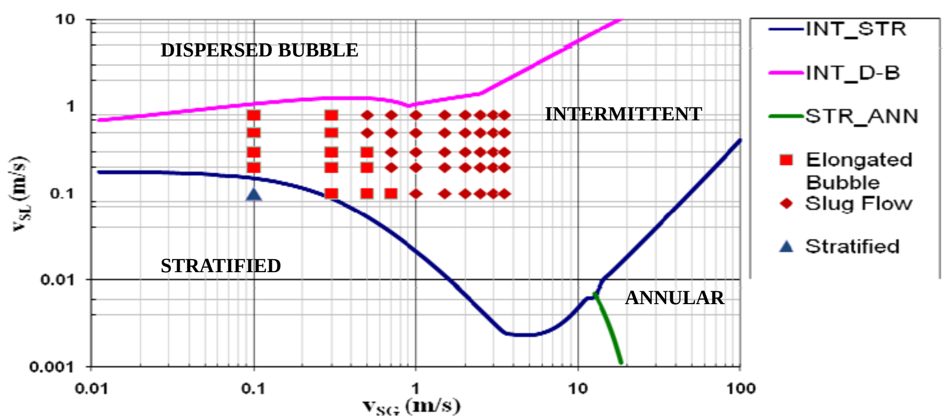
Unified Model Flow Pattern…
181 cP



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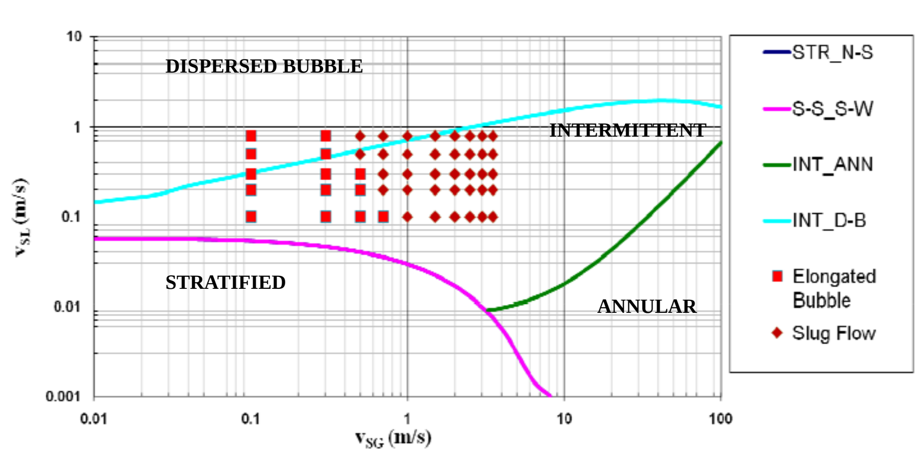
Taitel & Dukler Flow Pattern Map
585 cP



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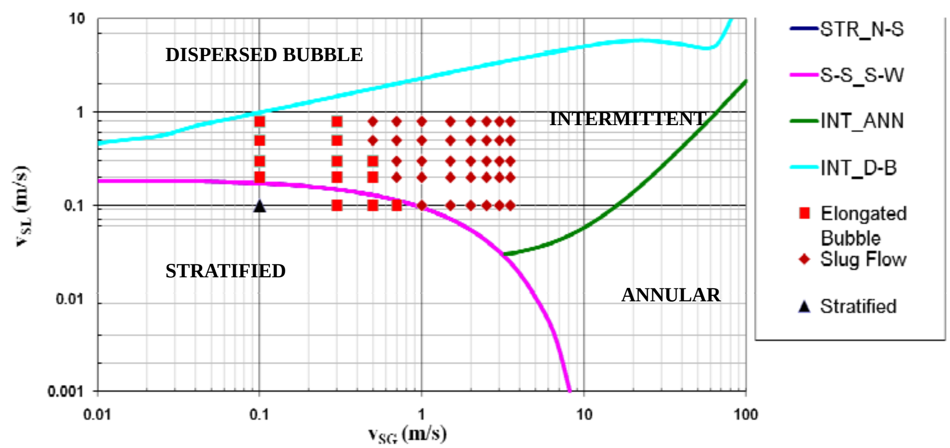
Taitel & Dukler Flow Pattern Map…
181 cP



Fluid Flow Projects

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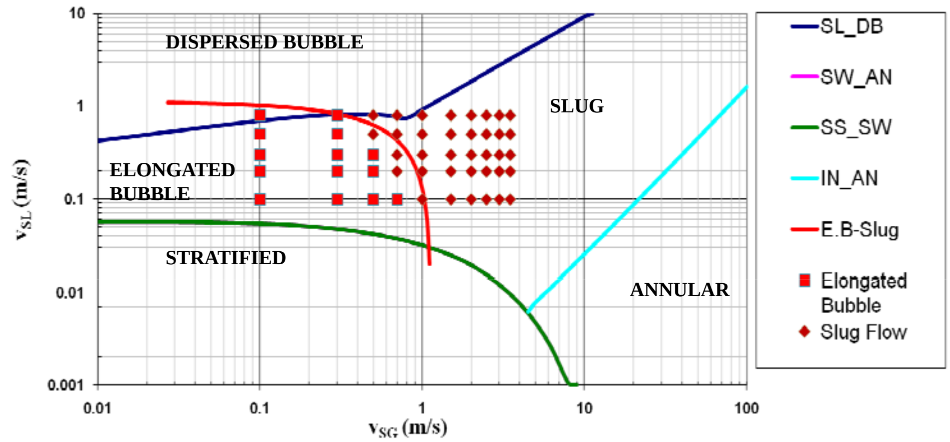
Barnea Flow Pattern Map
585 cP



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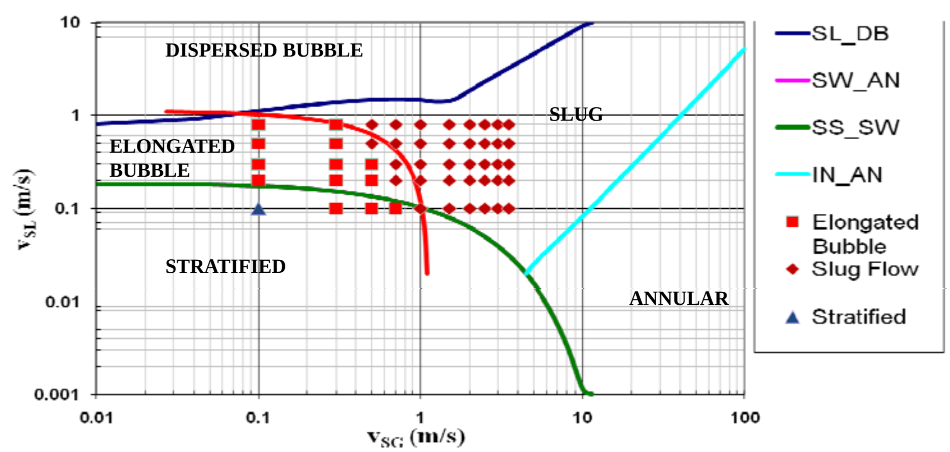
Barnea Flow Pattern Map…
181 cP



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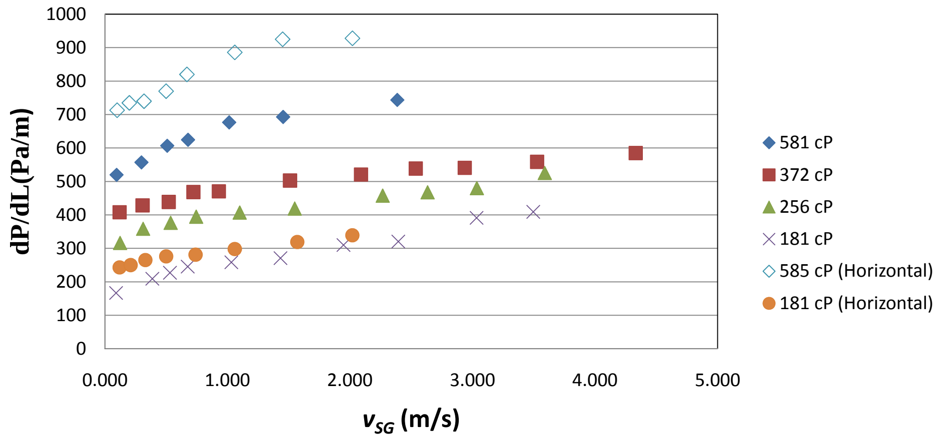
Pressure Gradient
v_{SL} - 0.1 m/s



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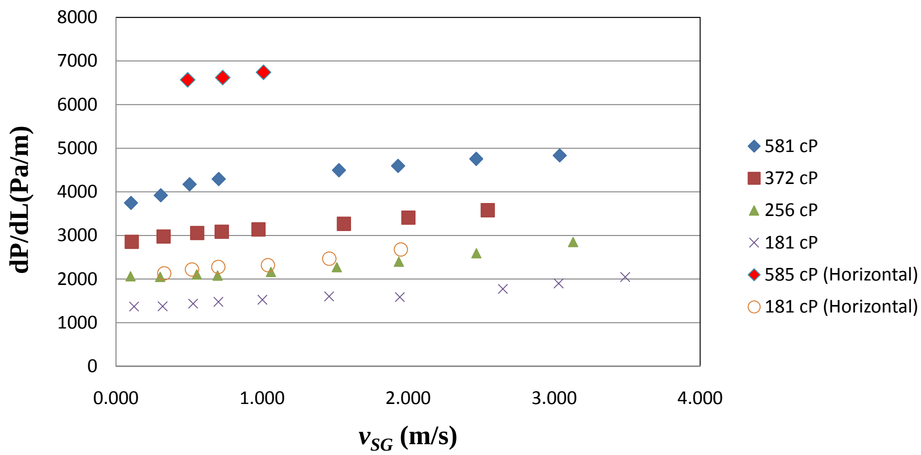
Pressure Gradient…
v_{SL}- 0.8 m/s



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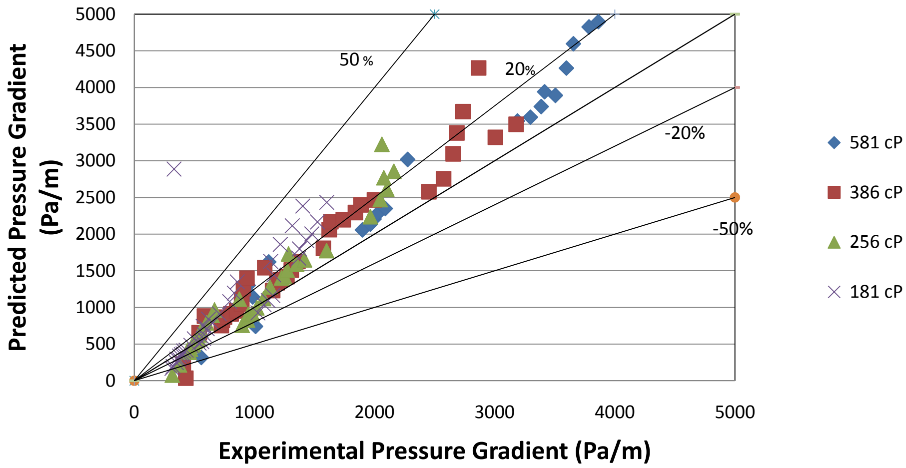
TUFFP Model Comparison



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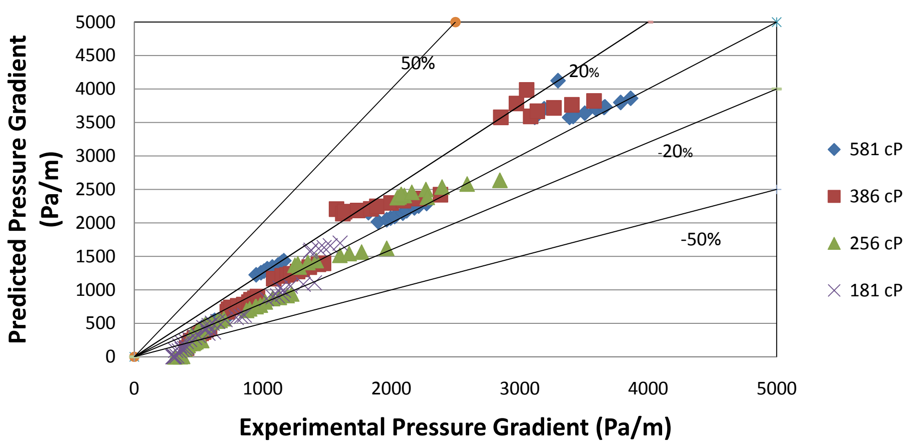
Xiao Model Comparison



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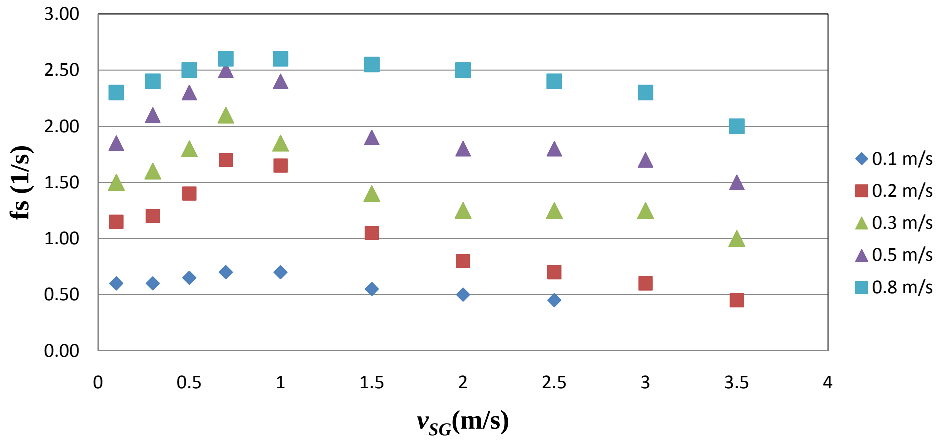
Slug Frequency
585 cP



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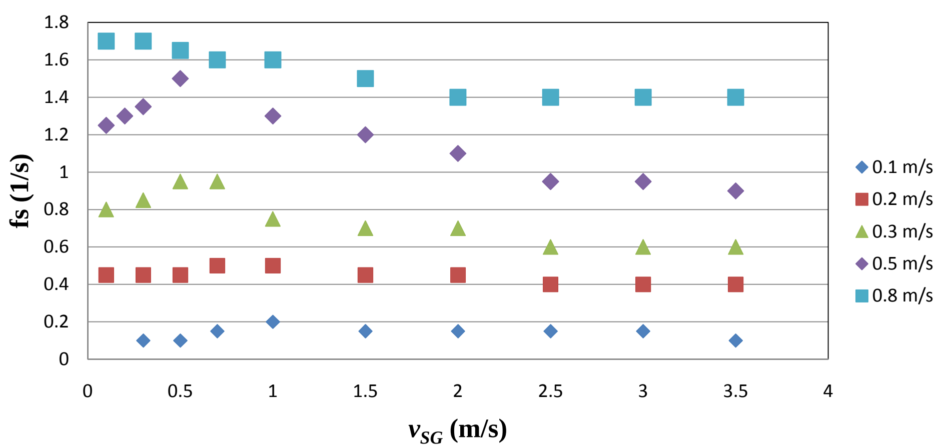
Slug Frequency…
181 cP



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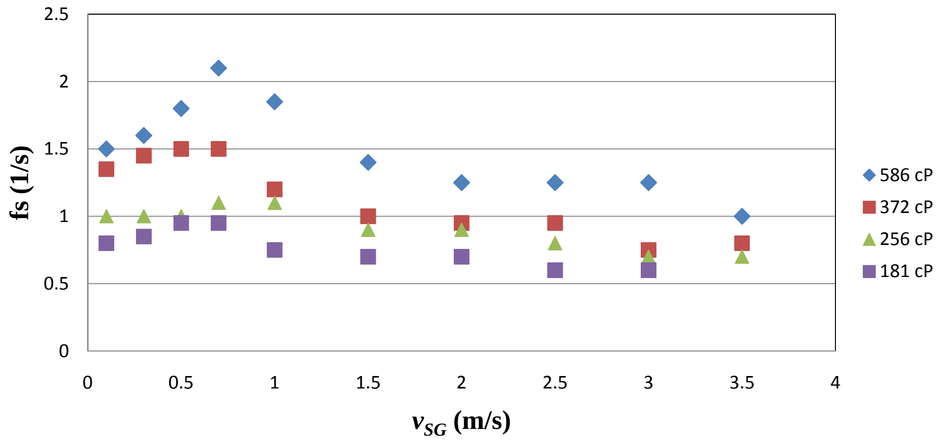
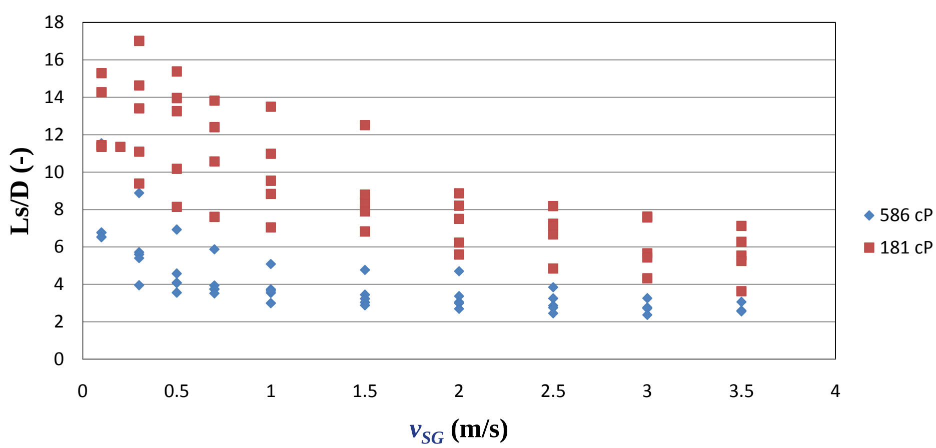
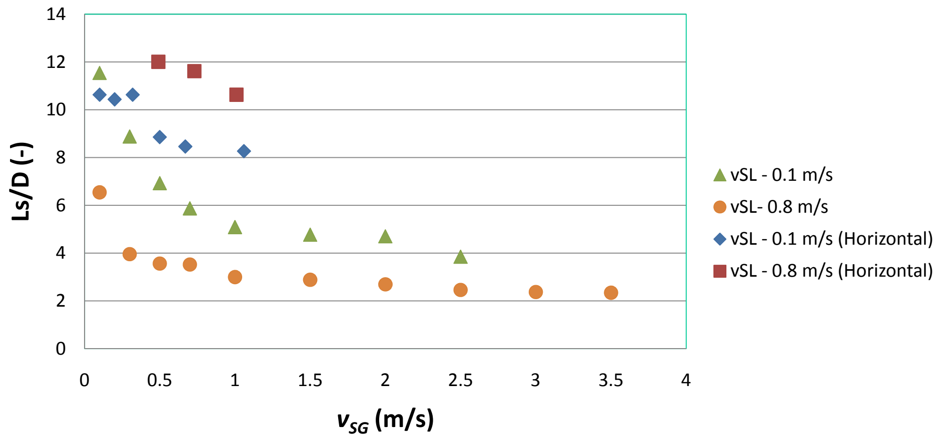
Slug Frequency…
v_{SL} - 0.3 m/s



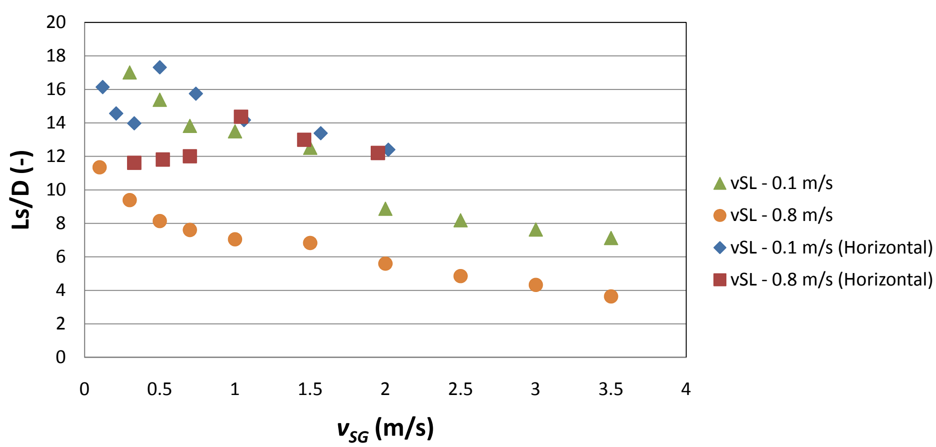
Dimensionless Slug Length



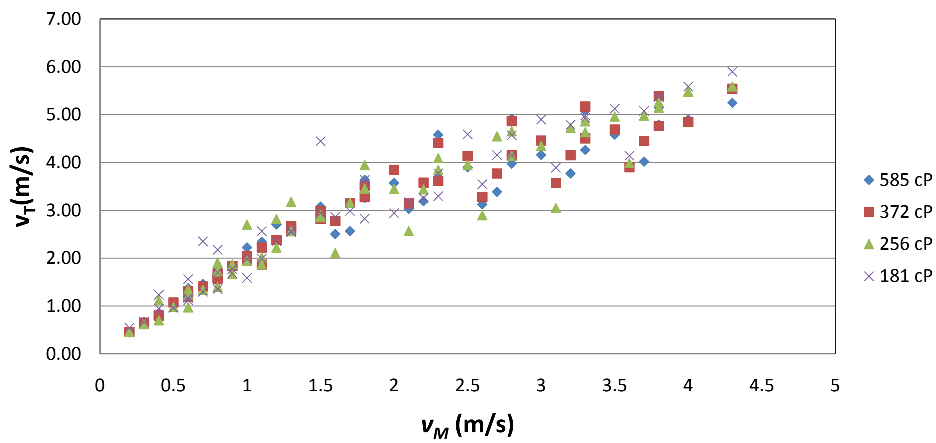
Dimensionless Slug Length…
585 cP



Dimensionless Slug Length…
181 cP



Translational Velocity vs. Mixture Velocity



Conclusion

- Experimentation for Two Phase Flow Characteristics on -2° Inclination Completed
- Flow Characteristics
  - Flow Pattern
  - Differential Pressure
  - Slug Length
  - Slug Frequency
  - Translational Velocity

Future Tasks

- Liquid Holdup
- Experimentation for +2° Inclination
- Comparison with Model/Correlation
- Develop Correlations If Required

Questions/Comments

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

Benin Chelinsky Jeyachandra

Project Completion Dates

Literature Review	Ongoing
Experimental Program for -2° Inclination	December 2010
Facility Modification for +2° Inclination	March 2011
Experimental Program for +2° Inclination	April 2011
Data Evaluation	June 2011
Final Report	August 2011

Objectives

The main objectives of the study are:

- Study pipe inclination angle effects on oil-gas two-phase with high oil viscosity, experimentally;
- Evaluate models/correlations and suggest improvements if necessary.

Introduction

Nearly 70% of the available oil reserves correspond to heavy oils, which possess high density and viscosity. Depletion of lighter hydrocarbon resources has increased the importance of high viscosity oils. A thorough knowledge on the flow behavior of high viscosity oils is required to design and optimize production facilities. The existing multiphase flow models were developed using data collected for low viscosity oils. Hence, these models inherently neglect the effect of viscosity on flow characteristics of multiphase flow.

TUFFP initiated a research campaign to understand the gas-liquid in 2003. Gokcal (2005) experimentally studied the effects of high viscosity on two phase oil-gas flow. He observed a marked difference between the experimental results and the model predictions. Intermittent slug and elongated bubble flow were observed to be the dominant flow pattern. Later, Gokcal (2008) conducted experiments and developed correlations for two phase slug flow characteristics, taking into account, the effects of viscosity. The parameters that studied were pressure gradient, drift velocity, transitional velocity, and slug length and frequency. All tests were conducted for horizontal flow and oil viscosities range from 121 cp to 1,000 cP. Recently, Kora (2010) conducted experiments and developed correlations for slug liquid holdup in horizontal high viscosity oil-gas flow.

The next step in understanding of high viscosity oil-gas two-phase flow is the investigation of the inclination angle effect on the different flow parameters and slug characteristics.

Activities Summary

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

Experiment Facility

The experimental facility for this study is the indoor high viscosity oil-gas two phase flow loop of TUFFP. The diameter of flow loop is 2-inch and the facility can be inclined from -2° to +2° from horizontal. The parameters studied are inclination angle and viscosity. To accurately control the viscosity of oil, the facility is equipped with a heating and a cooling system. The viscosity range varied from 585 to 181 cP. The superficial liquid velocity varied from 0.1 to 0.8 m/s and the superficial gas velocity ranged from 0.1 to 3.5 m/s.

The two-phase flow characteristics that are being studied are flow pattern, differential pressure gradient, slug length, slug frequency and translational velocity.

A summary of results obtained for -2° inclined flow is given below.

Flow Pattern

Intermittent flow (elongated bubble and slug flow) was the most dominant flow observed for -2° inclined two phase flow. Stratified flow pattern was observed for 181 cP and v_{SL} and v_{SG} of 0.1 m/s, while stratified wavy flow pattern was observed at 372 cP and v_{SL} of 0.1 m/s and v_{SG} of 5 m/s.

Pressure Gradient

Differential pressure transducers were used to measure the pressure gradient. From the data, it was observed that the pressure gradients increase with increasing superficial oil and gas velocity. As expected, pressure gradient for inclined pipe was small as compared to horizontal pipe flow, owing to the contribution of the gravitational pressure gradient.

Translational Velocity

The laser sensors were used to collect data for translational velocity. Cross correlation technique was utilized to quantify time-lag between the two sensors. The time-lag along with the distance of separation of two lasers give the translational velocity. Linear relationship was observed between the mixture and the translational velocities. For low mixture velocities (v_M<1.5 m/s), the slope of the best fitted line is 1.993, which is in agreement with laminar flow high viscosity oils observations. For high mixture velocities (v_M>1.5 m/s), large scattering of the data is observed, which can be due to pseudo slugs observed under this conditions. The data is currently being further analyzed.

Slug Length

Capacitance sensors were used to acquire slug length data. A VBA macro was developed to calculate the average slug length from individual slug length distribution. It was observed that as the v_{SL} and v_{SG} increases, the slug length decreases gradually. It was also observed that as the viscosity increases, the slug length decreases. The range of slug lengths varied from 2D to 18D.

Slug Frequency

Capacitance sensor data were used to calculate the slug frequency. It has been observed that, as the viscosity increases, the slug frequency increases. A possible reason is that for higher viscosities the liquid height in the pipe is higher, increasing the chance of any wave to become a slug.

For a fixed v_{SL}, as the v_{SG} increases, slug frequency increases reaching a maximum around v_{SG} =0.7 m/s, decreasing for higher velocities. The initial increase in slug frequency is expected because higher superficial gas velocity increases the chance of forming waves that will bridge the cross section of pipe forming slugs. As the superficial gas velocity is further increased, the liquid holdup in the pipe decreases resulting in slug frequency reduction.

Liquid Holdup Capacitance sensors are used for calculation of slug liquid holdup. Static and dynamic calibration of capacitance sensor has to be completed for obtaining the slug liquid holdup. This will be done in the next period.

Facility Modification

The loop is already inclined using a pivot arrangement. Additional supports are being provided. A new base has to be designed for the quick closing valves to adjust with inclination angles. In addition to the existing ring type capacitance sensor, a two wire capacitance sensor has also been integrated to the facility, before experimentation in +2° inclination commenced. Trial runs on the same shows great promise and it can replace the laser sensors for translational velocity calculations.

Conclusions

Experimentation in -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. Data analysis is currently underway.

Future Planned Activities

The experimentation in +2° will commence shortly. Dynamic calibration of capacitance sensor will be started after experimentation on +2° pipe inclination is completed. Data analysis will be started concurrently.

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

References

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

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

Kora, Y. "Effects of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes," Ms Thesis, The University of Tulsa, Tulsa, OK. (2010).

Fluid Flow Projects

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

Rosmer Brito

Advisory Board Meeting, May 12, 2011

Outline

- General Objective
- Literature Review
- Justification
- Project Plan
- Experimental Range
- Facility Modifications
- Instrumentation
- Future Tasks

General Objective

- Perform an Experimental and Modeling Study of Oil-Gas Two Phase Flow to Investigate the Effects of Medium Viscosity Oil (20 cP - 200 cP) on Flow Pattern, Pressure Drop, Liquid Holdup and Slug Characteristics

Literature Review

- Effect of Liquid Viscosity on Two Phase Flow Behavior
  - Colmenares *et al. (2001)*
    - μ_O = 480 cP
    - Slug Flow Pattern Enlarged when the Oil Viscosity Increased
  - Gokcal *et al. (2006)*
    - 181 cP $\leq \mu_O \leq$ 587 cP
    - Pressure Gradients Increase with Increasing v_{SG} and μ_O
    - Discrepancies with Existing Models to Predict dP/dL and H_L

Literature Review …

- **Effect of Liquid Viscosity on Slug Flow Characteristics**
  - **Nadler and Mewes *(1995)***
    - **1 cP ≤ μ_L ≤ 37 cP**
    - **Averaged Liquid Holdup and the Liquid Holdup within the Film Zone Are Higher for Oil-Air Slug Flow**
  - **Gokcal *et al. (2010)***
    - **181 cP ≤ μ_O ≤ 587 cP**
    - **Slug Frequency is a Strong Function of Liquid Viscosity**

Literature Review …

- **Effect of Liquid Viscosity on Slug Flow**
  - **Rosa *et al. (2004)***
    - **1 cP ≤ μ_L ≤ 27 cP**
    - **Average Slug, Bubble Length and Coalescence Rate Decrease with Increasing Liquid Viscosity**
    - **Bubble Front Velocity and Slug Frequency Increased with Increasing Liquid Viscosity**

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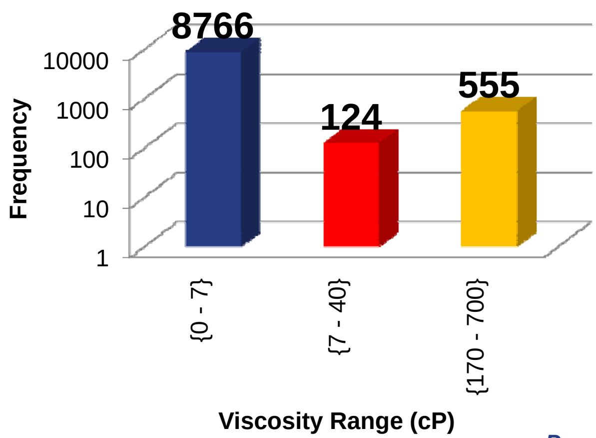
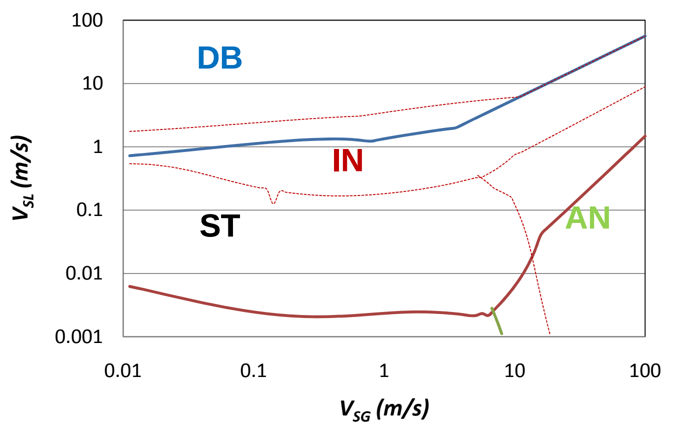
Justification



Pereyra et al.

Justification …



Flow Pattern Map. 200 cp vs. 1cp
Unified Model

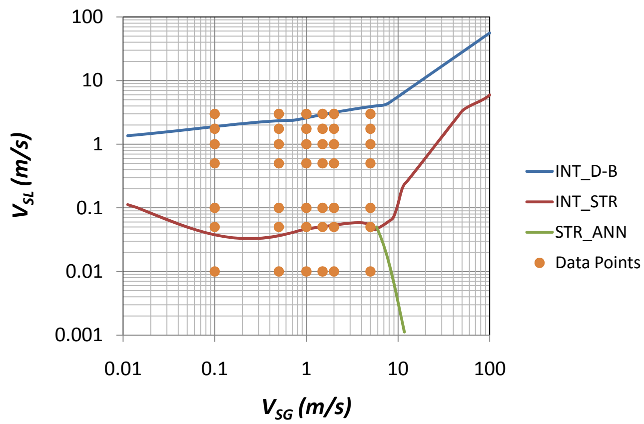
Project Plan

- Experimental
  - Range of Experiments
  - Facility Modifications
  - Fluid Selection
  - Experimental Program
  - Data Acquisition and Analysis
- Modeling
  - Model Performance
  - Closure Relationship Development

Experimental Range

- Facility: Indoor Two Phase Oil-Air Flow
- Fluids: Air and Mineral Oil
- Horizontal Pipe
- 50.8 mm Pipe ID
- Oil Viscosities Range: 20-200 cp
- v_{SL} from 0.01 m/s to 3 m/s
- v_{SG} from 0 to 5 m/s

Experimental Range …



Flow Pattern Map (20 cp)
Unified Model

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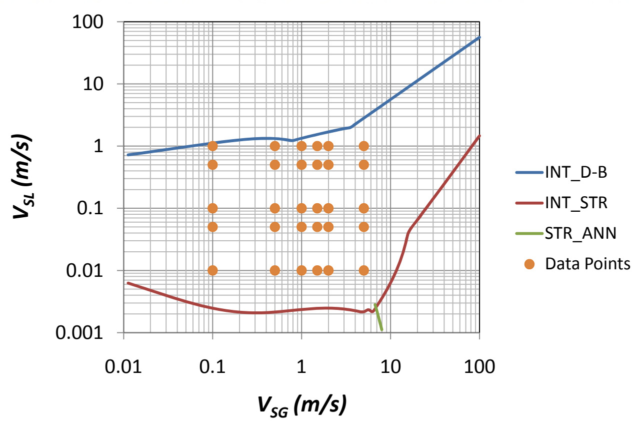
Experimental Range …



Flow Pattern Map (200 cp)
Unified Model

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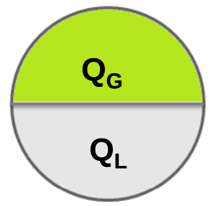
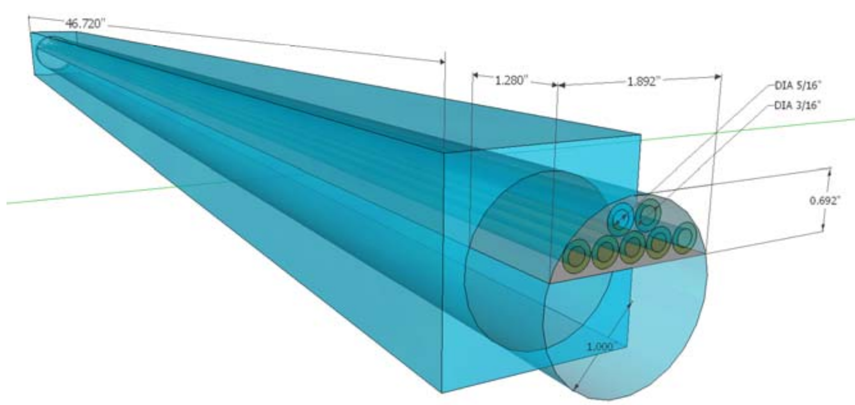
Facility Modifications



Current Inlet Configuration

Facility Modifications …



Proposed Inlet Configuration

Facility Modifications …

- Limited Tests with the High Viscosity Oil and Horizontal Pipe Will be Run with the New Inlet to Compare the Results with Previous Results

Instrumentation (Existing)

- Two Capacitance Sensor
- Two Laser Sensors
- High Speed Camera
- (4) Pressure, (3) Temperature and (2) ΔP Transducers
- Flow Meter for Gas and Liquid

Flow Pattern, Pressure Drop, Liquid Holdup and Slug Characterization

Fluid Flow Projects
Advisory Board Meeting, May 12, 2011

Instrumentation (Additional)

- High Speed Camera
  - Record Flow Pattern at the Inlet
- Dynamic Pressure Transducer
  - Measure Dynamic Pressure Pulsations
- Capacitance Sensors
  - Two More Capacitance Sensors to Evaluate Flow Pattern Evolution Along the Test Section
- Sonic Sensor

Near Term Tasks

- Construction of New Inlet Configuration
- Conduct Inlet Effect Tests
- Validation of Sonic Devices for Slug Flow Characterization
- Data Automation
- Oil Selection and Characterization (μ vs. T and ρ vs. T)

Long Term Tasks

- Conduct Experiments for Medium Viscosity (20-200 cp)
  - Single Phase Flowing Condition
  - Two Phase (Oil-Air) Flowing Condition
- Model Verification or Develop New Ones If Necessary

Project Schedule

- Literature Review
  (Ongoing)
- New Inlet Construction and Verification Test
  (Apr-Jun-2011)
- Oil Selection and Characterization
  (Apr-2011)
- Experimental Design and Program Execution
  (April-Dec-2011)
- Model Verification or develop New Ones
  (Feb-2012)

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

Rosmer Brito

Project Completion Dates

Literature Review	Ongoing
New Inlet Design, Construction and Verification Test	June 2011
Oil Selection and Characterization for Medium Viscosity	April 2011
Experimental Matrix Design	April 2011
Data Processing Automation	June 2011
Experimental program Execution	January 2012
Model Verification or Develop New Ones (if Necessary)	May 2012

Objectives

Perform an experimental and modeling study of oil-gas two phase flow in horizontal pipe to investigate the effects of medium viscosity oil (20 cP < μ_O < 200 cP) on two-phase flow parameters such as flow pattern, pressure drop, liquid holdup, and slug characteristics.

Introduction

Gas-liquid two-phase flow in pipes is a common occurrence in the petroleum industry. Accurate prediction of the flow pattern, pressure drop and liquid holdup is imperative for the design of production and transport systems. A variety of flow patterns appears in two-phase flow, depending on the gas and liquid flow rates, pipe diameter and inclination, and fluid properties.

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. If needed new closure relationships or models need to be developed.

Activities Summary

In the last period, several activities have been carried out for this project and a description of the most important achievement are presented in the next sections.

Literature Review

An extensive literature review of two-phase flow characterization for medium oil viscosities has been carried out. The most relevant studies are summarized next.

Experimental Studies for Medium Oil Viscosity

Pereyra *et al.* (2011) carried out a compilation of all the available gas-liquid flow pattern experimental data for different oil viscosity ranges from lower viscosity (1 cP – 7 cP) to high viscosity (140 cP – 700 cP), these data points are distributed in 8677, 121 and 555 data points for low viscosity, medium viscosity and high viscosity, respectively. The analysis shows that a few experiments for medium viscosity are available to validate the current flow pattern, pressure drop and liquid hold up models.

Effect of Viscosity on Two-Phase Flow Behavior

Gokcal *et al.* (2006) conducted an experimental study to investigate the effect of high oil viscosity on the two phase oil-gas behavior. The viscosity range was from 181 cP to 587 cP. He concluded that all the flow patterns can exist for the range of the viscosities studied. The comparison of experimental data for pressure gradient and liquid holdup against the Zhang *et al.* unified (2002) and Xiao *et al.* (1990) mechanistic models show that the performances of the models are not sufficient for high viscosity oils.

Effect of Liquid Viscosity on Slug Flow Behavior

Nadler and Mewes (1995) conducted an experimental study to investigate the effect of the liquid viscosity on the phase distribution in slug flow for horizontal pipes. The viscosity range was from 14 cP to 37 cP. Their results indicated that the averaged liquid holdup and the liquid holdup within the film zone are higher for oil-air slug flow compared with water-air slug flow.

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

Al-Safran *et al*. (2005) carried out a probabilistic and mechanistic modeling to develop a predictive model for fully developed slug-length distribution in a horizontal pipeline. Two empirical relationships for slug length average and standard deviation were developed. The statistical analysis revealed that, in addition to pipe diameter and mixture velocity, the volumetric liquid film flow rate and the momentum exchange between the slug body and the liquid film are significantly correlated to the average slug length. On the other hand, the slug-length standard deviation was found to have a significant correlation with film liquid holdup which in previous studies has been found to be strong depended of the liquid viscosity.

Gokcal *et al.* (2010) conducted an experimental study to evaluate the effects of high oil viscosity on slug frequency for horizontal. The experiments were performed at oil viscosity between 181 cP and 589 cP. Experimental observations revealed that slug frequency appear to be a strong function of liquid viscosity. However, previous slug frequency closure models do not show any explicit dependency on liquid viscosity. A new closure model taking into account the viscosity effects for horizontal pipe on slug frequency were proposed.

Kora *et al.* (2010) investigated the effects of high oil viscosity on slug liquid holdup in horizontal pipes. The viscosity range was from 181 cP to 587 cP. No significant change in slug liquid holdup was observed with increasing oil viscosity. Several correlations and mechanistic models show good agreement with the measured slug liquid holdup data for mixture velocities lower than 2 m/s.

The previous literature review shows that several experimental and modeling studies indicated that liquid viscosity has a significant effect in the two-phase flow behavior and slug characteristics. 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.

Project Plan

The following project plan is proposed:

Experimental

Experimental Range

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 range will be from 20 to 200 cP. The superficial liquid velocity will vary from 0.01 m/s to 3 m/s and from 0.01 m/s to 1 m/s for the lowest and highest viscosities values respectively. The superficial gas velocity will vary from 0 to 5 m/s.

Facility Modifications

A new inlet design will be use to run the experiments. The new inlet has the same inside diameter of 50.8 mm and 4 ft of length. Inside of the inlet, a plate divides the air an oil entrance. The oil and gas will have ¾ and ¼ of the total area to flow respectively. In addition, along the gas flow 7 capillary pipes are placed to reduce the gas turbulence and avoid the generation of premature slugs at the facility entrance.

Instrumentation

Two capacitance sensor, two laser sensors, one sonic sensor at the test section will be used for the slug characterization (average liquid holdup, Taylor bubble velocity, slug frequency, slug liquid holdup, slug length). A high speed camera will be used to characterize the flow pattern. In addition, three temperature, four pressure and two differential pressure transducers are installed along the test section. Moreover, at the entrance of the test section, a high speed camera and a dynamic pressure transducer will monitor the flow behavior when oil and air are mixed. Finally, two additional capacitance sensors will be installed along the test section to evaluate flow pattern evolution along the test section and better determine flow development.

Experimental Program

First, a limited number of tests with the high viscosity oil (181 cP < μ_O < 587 cP) and horizontal pipe will be run with the new inlet configuration to compare the results with previous experimental data under the same experimental conditions. In addition, this set of experiments will be used to test a sonic sensor for slug flow characterization.

The second set of experiments will be run with the medium oil viscosity under single-phase flowing conditions. This information will be used to check the optimal operation of the facility and to calculate the viscosity values for different temperature values and compare these with the previous oil characterization.

The final set of experiments will be run viscosities from 20 to 200 cP. These results will be used to validate the performance of existing flow pattern, pressure gradient and holdup prediction models.

Modeling

Model Performance

The experimental results will be used to validate the performance of existing flow pattern, pressure gradient and holdup prediction models.

Model Improvement or Development

If the performance analysis indicates a poor performance of the existing models, new models or closure relationships will be developed.

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Fluid Flow Projects

Investigation of High Viscosity Oil Two-Phase Slug Length in Horizontal Pipes

Eissa Al-safran (KU/KOC)

Advisory Board Meeting, May 12, 2011

Outline

- Introduction
- Flow Visualization
- Data Analysis
- Physical and Theoretical Viscosity Effect
- Modeling
- Future Work

Significance

- Pipeline Design (Sizing and Routing)
  - Pressure Drop
  - Liquid Volume
- Facility/Equipment Design
  - Instantaneous Liquid Rate at Pipe Outlet is 5-20 x Average Rate
  - Slug Catchers
  - Multiphase Pumps
  - Multiphase Meters

Significance …

- Flow Assurance
  - Terrain Slugging
  - Erosion/Corrosion
- Mechanical Integrity
  - Piping System
  - System Components

Literature Review

- No Literature is Found on High Viscosity Oil Two-phase Slug Length
- Low Viscosity Oil Slug Length is Strongly Correlated to Pipe Diameter, and Insensitive to Other Parameters
- Low Viscosity Oil Slug Length
  - Smallest Near the “Center” of Slug Flow Region on Flow Pattern (FP) Map
  - L_s Increases Near Transition Boundaries

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Literature Review ...

- High Viscosity Effect on Liquid Holdup in Film and Slug Regions-Direct Relationship
- High Viscosity Effect on Slug Frequency-Inverse Relationship
- Increase of Slug Frequency and Slug Liquid Holdup Results in Short Slugs

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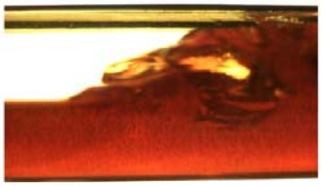
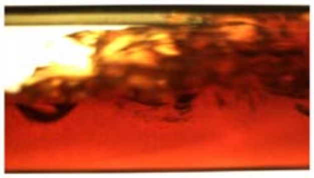
Flow Visualization

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



μ=0.590 Pa.s



μ=0.182 Pa.s

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Flow Visualization ...

➢ Slug body

μ=0.590 Pa.s

μ=0.182 Pa.s

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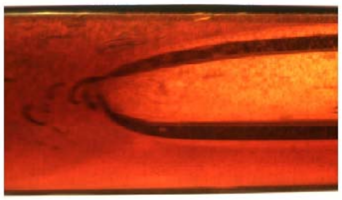
Flow Visualization ...

➢ Slug Tail



μ=0.590 Pa.s

μ=0.182 Pa.s

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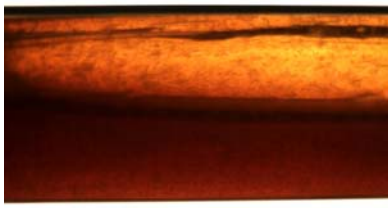
Flow Visualization ...

- Film Region (v_{SL}=0.1 m/s, v_{Sg}=2 m/s, μ=0.26 Pa.s)



Developing film

Developed film

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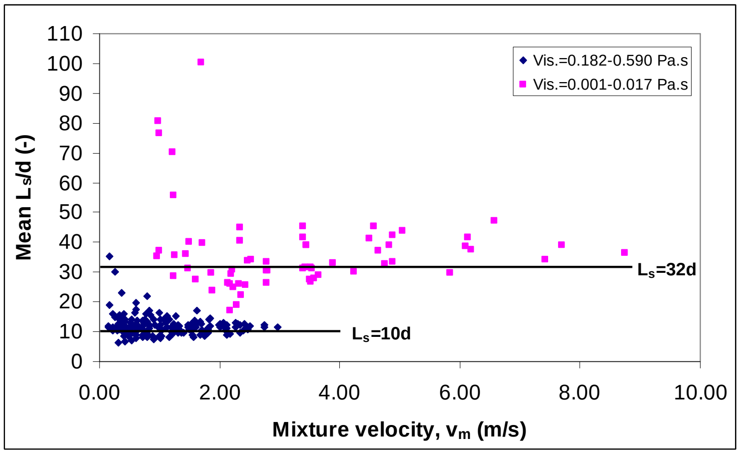
Data Analysis

- Comparison (Kouba (1986), BP Loop (2001), Alsafran (2003), Gokcal (2008))



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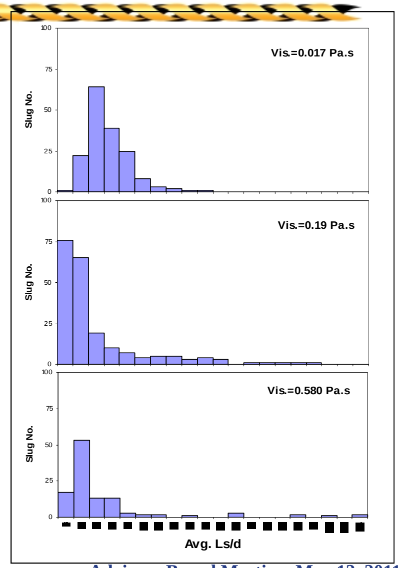
Data Analysis ...

- Slug Length Distribution Comparison (Low Viscosity vs. Moderate vs. High Viscosity)

v_{SL}=0.3 m/s
v_{Sg}=1.5 m/s



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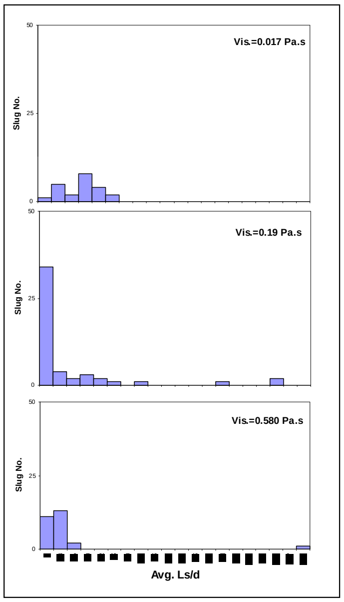
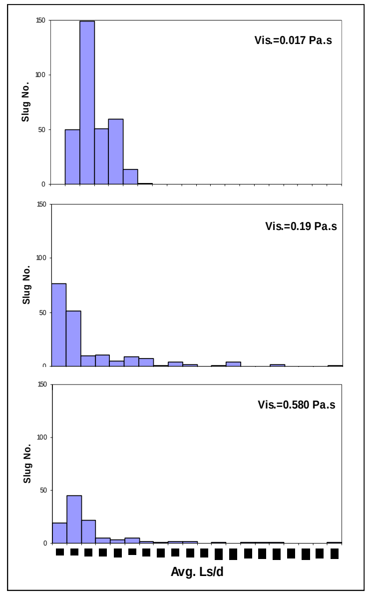
v_{SL}=0.05 m/s, v_{Sg}=2.1 m/s



v_{SL}=0.3 m/s, v_{Sg}=2.1 m/s



Data Analysis ...

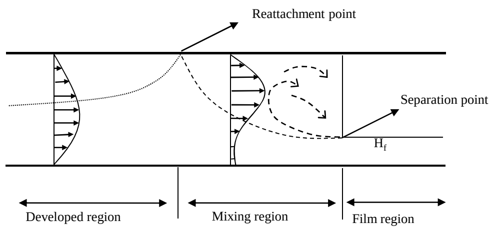
- **Analysis of Variance (ANOVA) to Test the Following Hypothesis:**

$$H_0 : \mu_{low} = \mu_{mid} = \mu_{high}$$

  - **Calculate p-value and Set Significance Level (α=0.10), i.e. 90% Confidence**
  - **Calculated p-value<α, Thus Reject H_0**

Physical Viscosity Effect

- Dukler *et al.* (1985) Proposed Minimum Slug Length Physical Model



  - Sudden Expansion at Separation Point
  - New Wall Boundary at Reattachment Point
  - Downstream a Fully Developed Velocity Profile is Formed and Flow "Memory" Vanishes

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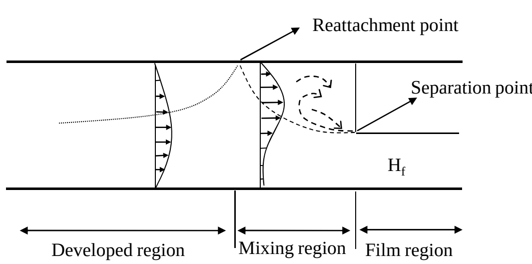
Physical Viscosity Effect ...

- Proposed High Viscosity Liquid Physical Model
  - Thick Film-Less Expansion (Jet Velocity)
  - Less (Short) Front Mixing Intensity
  - Smaller Velocity Profile and Maximum Velocity

$$v_z = \frac{\Delta P \times R^2}{4\mu L}\left[1-\left(\frac{r}{R}\right)^2\right]$$



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Theoretical Viscosity Effect

$$L_s = \frac{v_s}{\upsilon_s \left(H_{LLS} - H_{LTBe}\right)}\left[\left(\frac{W_L}{\rho_L A_p v_s} - H_{LTBe}\right) + c\left(H_{LLS} - H_{LTBe}\right)\right]$$

First Term: $\left[\frac{v_s \downarrow}{\upsilon_s \uparrow \left(H_{LLS} \uparrow - H_{LTBe} \Uparrow\right)\downarrow}\right]\downarrow$

Second Term: $\left[\left(\frac{W_L \rightarrow}{\rho_L(\rightarrow) A_p(\rightarrow) v_s(\downarrow)}\right)\uparrow - H_{LTBe} \Uparrow\right]\downarrow$

Third Term: $\left[c(\rightarrow)\left(H_{LLS} \uparrow - H_{LTBe} \Uparrow\right)\right]\downarrow$

Thus, Slug Length Decreases with Increasing Liquid Viscosity

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Modeling

- Woods and Hanratty (1996) (Low Viscosity)

$$\frac{f_s D}{v_{SL}} = 1.2\left(\frac{L_s}{d}\right)^{-1} \quad \text{......................} \quad (1)$$

- This Study (High Viscosity)

$$\frac{f_s d}{v_{SL}} = 1.94\left(\frac{L_s}{d}\right)^{-1} \quad \text{......................} \quad (2)$$

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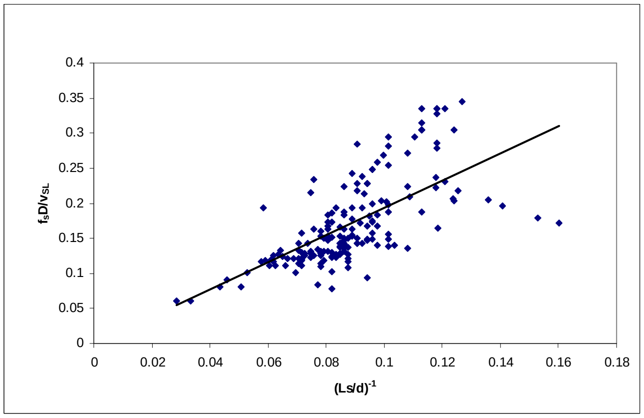
Modeling ...



Modeling ...

- **Wallis (1969) Presented Dimensional Analysis for Inertia and Viscous Forces**

$$F_{rd} = \frac{v_d}{(gd)^{0.5}} \sqrt{\frac{\rho_L}{(\rho_L - \rho_G)}} \quad \text{.....................} \ (3)$$

$$N_\mu = \frac{v_d \mu_L}{gd^2(\rho_L - \rho_G)} \quad \text{.....................} \ (4)$$

Modeling ...

- Combing Froude and Viscosity Numbers

$$N_f = \frac{F_{rd}}{N_\mu} = \frac{d^{3/2}\sqrt{\rho_L(\rho_L-\rho_G)g}}{\mu_L} \quad \text{.................... (5)}$$

- Gokcal *et al.* (2009) showed

$$f_s = 2.623\left(\frac{N_f^{-0.612} v_{SL}}{d}\right) \quad \text{.................... (6)}$$

Modeling ...

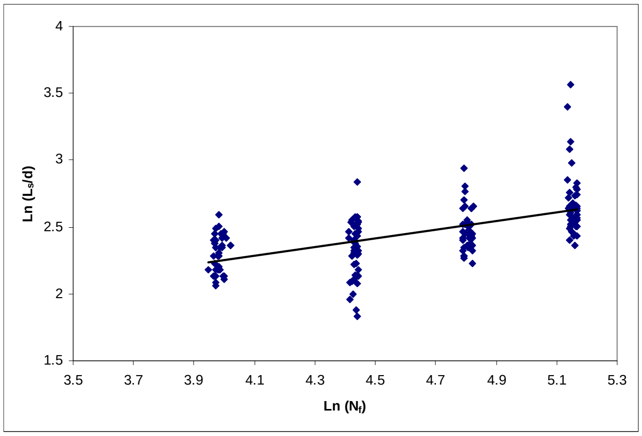
- Combing Eqs. 2, 5 and 6, and Solving for Dimensionless Slug Length

$$\frac{L_s}{d} = \beta_0 N_f^{\beta_1} \quad \text{...................... (7)}$$

- Linearizing and Fitting the Proposed Model against High Viscosity Data

$$\frac{L_s}{d} = 2.63 N_f^{0.321} \quad \text{...................... (8)}$$

Modeling ...



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Modeling ...

- **Model Statistical Evaluation**
  - **Overall Model Evaluation**

Model df	Error df	SSE	MSE	R^2
1	161	6.43	0.200	0.32

  - **Model Coefficient Evaluation**

Variable	Coef.	Standard Error	t-statistics	p-value	Lower 95% CI	Upper 95% CI
$Ln(\beta_0)$	0.966	0.170	5.800	0.000	0.650	1.310
β_1	0.321	0.036	8.730	0.000	0.246	0.390

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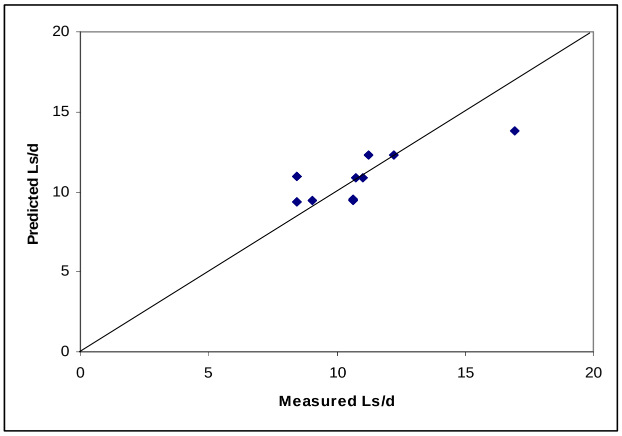
Modeling ...

- Model Validation
  - 10 data points Selected Randomly and Removed From Model Development Process
  - Statistical Error Analysis Results

Stat. Parameter	Value
APE (%)	1.72
AAPE(%)	9.8
SD(%)	13.6

Modeling …

- Model Validation …



Modeling …

- **Model Comparison**
  - **10 data points Selected Randomly and Removed From Model Development Process**

Correlation	APE (%)	AAPE (%)	SD (%)
Brill *et al*. (1980)	295.2	295.2	78.1
Scott *et al*. (1981)	344.6	344.6	83.3
Norris (1982)	298.9	298.9	74.8
Barnea & Brauner (1985)	203.7	203.7	56.9
Dukler *et al*. (1985)	89.8	89.8	35.6
Present Study	1.7	9.8	13.6

Conclusion

- **Slug Structure (Front and Back) in High Viscosity Liquid Condition is Different than Low Viscosity Condition**
- **This Structure Results in Shorter Slugs**
- **Average Stable Slug Length is equal 10d and Remains Constant above v_m=0.5 m/s**

Conclusion . . .

- Slug Length Distribution is Truncated and Heavily Skewed to the Right
- Large Film Thickness and Small Centerline Velocity and Velocity Profile Shorten the Required Slug Length to Reach Stable Slug
- High Liquid Viscosity Slug Length Empirical Correlation is Proposed, Validated and Compared with Existing Correlations

Conclusion . . .

- Model Validation Study Show APE=1.7%, AAPE=9.8% and SD=13.6%
- Comparison Study Show Proposed Model Outperform Large Diameter and Small Diameter Existing Correlations

Investigation of High Viscosity Two-Phase Slug Length in Horizontal Pipes

Eissa Al-safran

Project Completion Dates

Literature Review and Data Analysis – Completion Date .... September 2009
Physical Modeling – Completion Date .... January 2010
Modeling – Completion Date .... April 2010
Model validation and comparison – Completion Date .... October 2010
Write up – Completion Date .... January 2011

Objectives

The objective of this project is to understand the effect of high viscosity liquid on average slug length and slug length distribution in horizontal pipes. Additional objective is to develop physical and mathematical models to explain and predict average slug length in horizontal high viscosity two-phase flow.

Introduction

Gas-liquid two-phase flow in pipes occurs at production and transportation facilities. The most common type of flow patterns in field operation for horizontal and near horizontal pipelines is the slug flow pattern. Slug flow is described by alternating liquid slugs and gas intervals, both of which when combined form what is called slug unit. Among all the slug flow characteristics, slug length is one of the most critical characteristic for system proper design and safe operation. For example, average slug length is important and preferred (over slug frequency) input parameter for mechanistic models to predict liquid holdup and pressure gradient. Furthermore, long slugs often cause operational problems, flooding of downstream facilities, severe pipe corrosion, structural instability of the pipeline, as well as production loss and poor reservoir management due to unpredictable wellhead pressures. Although several investigators studied the average and slug length distribution in pipes for light oil, a recent literature search on high viscosity two-phase slug length revealed no comprehensive study. However, few studies were found on the effect of high viscosity liquid on other two-phase slug flow characteristics such as liquid holdups and frequency, which can be related, implicitly, to slug length. This literature review suggests that under the condition of high liquid viscosity, slugs are less aerated and more frequent. Theoretically, these two characteristics result in short slugs. Furthermore, experimental data on light oil showed the inverse relationship between slug frequency and slug length, and between the slug liquid holdup and slug length. Therefore, from the limited literature review on high viscosity oil and the previous knowledge and experimental data on the relationships among slug flow characteristics, one can speculate an inverse relationship between liquid viscosity and slug length.

Activities Summary

The developed empirical model is function of the dimensionless inverse viscosity number as follows.

$$\frac{\overline{L}_s}{d} = 2.63 N_f^{0.321}$$

where,

$$N_f = \frac{Fr_d}{N_\mu} = \frac{d^{3/2}\sqrt{\rho_L(\rho_L - \rho_G)g}}{\mu_L}$$

Model validation and comparison

In this study, a lack of independent high liquid viscosity slug length data in the open domain to validated proposed model against was a challenge. Alternatively, ten data points of this study were randomly selected and eliminated from the process of model development to be used as independent data set for validation and comparison. Statistical error analysis shows that the model slightly overpredicts experimental data with about 10% absolute error. The analysis further shows that data dispersion around the model represented by standard deviation is low, 13.6%. Five correlations, namely Brill *et al*. (1980), Scott *et al*. (1981), Norris (1982), Branea and Brauner (1985) and Dukler *et al*. (1985) were compared with the present model which outperformed all correlations. In addition, existing correlations over-predicted average slug length with different magnitudes. Overall, model validation and comparison showed very good performance and the need for slug length correlation for high viscosity liquid condition, yet more independent data is required for further comparison.

Fluid Flow Projects

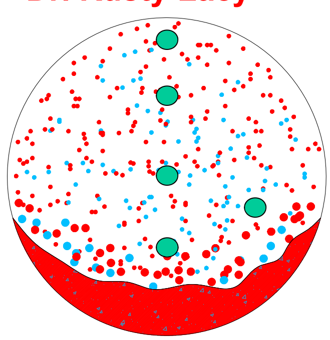
Low Liquid Loading Gas-Oil-Water in Pipe Flow

Kiran Gawas

Advisory Board Meeting, May 12, 2011

Previous ABM Suggestions

- Measurement of Entrainment Flux Closer to Pipe Wall - Dr. Rusty Lacy



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Previous ABM Suggestions …

- Investigation of Sudden Increase in Liquid Holdup for Upward Inclined Pipe - Mr. Richard Shea
- Preliminary Experiments To Check for This Phenomenon
- Experiments Close to Transition Point for Detailed Investigation

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Previous ABM Suggestions …

- Entrainment Fraction Correlation Based on Froude Number Approach - Dr. Tom Danielson
- Froude Number Related to Stability of Waves
- Not Accounted in Entrainment Fraction Correlations Available

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Outline

- Objectives
- Introduction
- Literature Review
- Preliminary Modeling Scheme
- 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 $m^3/MMsm^3$
- Widely Encountered in Wet Gas Pipelines
- Small Amounts of Liquid Influences Pressure Distribution – Hydrate Formation, Pigging Frequency, Downstream Equipment Design, etc.
- Transport of Additives

Literature Review

- Measurement Techniques
  - Phase Fractions
  - Liquid Film Velocity
  - Oil-Water Flow Pattern Identification
  - Size Distribution of Droplets Entrained in Gas Phase
- Modeling of Three Phase Flow
  - Oil-Water Flow
  - Gas Liquid Flow
  - Entrainment Fraction

Measurement Techniques

- Phase Fraction
  - Electrical Tomography (*George et al. 2001*)
  - Gamma Ray Tomography (*Froystein et al. 2005, Hale et al. 2005*, *Salgado et al. 2009, George et al. 2001*)
  - X-Ray Tomography
- Liquid Film Velocity
  - Pitot Tube/Isokinetic Sampling (*Khor et al. 1996, Vedapuri et al. 1997, Shi et al. 1999, 2000*)
  - Hot Wire Anemometry (*Farrar et al. 1995, Farrar Bruun 1996*)
  - Particle Tracking (*Kopplin 2004, Schubring et al. 2009*)

Measurement Techniques …

- Oil-Water Flow Pattern Identification
  - Flow Visualization
  - Capacitance Probe
- Size Distribution of Droplets Entrained in Gas Phase (*Al Sarkhi and Hanratty 2002*)
  - Flow Visualization Using High Speed Camera (*Patruno et al. 2010, Rodriguez and Shedd 2005, Fore et al. 2002*)

Modeling

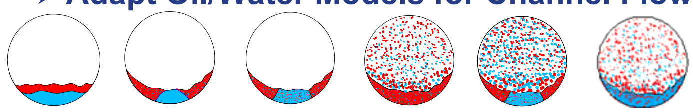
- Oil-Water Flow
  - Prediction of Oil-Water Flow Pattern
  - Transition from Stratified to Dispersion of Water in Oil (*Torres-Monzon 2006*)
  - Transition from Semi-Dispersed Flow to Completely Dispersed Flow (*Brauner 2001*)
  - Distribution of Droplets in the Dispersion (*Binder and Hanratty 1992, Mols and Oliemans 1998, Torres-Monzon 2006*)

Modeling …

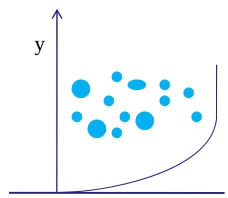
- Gas-Liquid Flow
  - f_L (*Fan et al. 2005, Vielma 2006, Troshko and Hasan 2001*)
    - Law of Wall
    - Turbulent Oil-Water Dispersion
  - Wetted Wall Fraction
- Entrainment Fraction
  - Rate of Atomization (*Pan and Hanratty 2002, Mantilla 2008*)
  - Droplet Transport (*Simmons and Hanratty 2001, Lecoeur et al. 2010, Baik and Hanratty 2003, Westende et al. 2007, Patruno et al. 2010, Brown et al. 2009, Mols and Oliemans 1998, Mito and Hanratty 2004*)
    - Ballistic Transport
    - Turbulent Diffusion

Modeling …

- Oil-Water Flow Pattern
  - Adapt Oil/Water Models for Channel Flow



- Friction Factor
  - Law of Wall Based on Flow Pattern



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

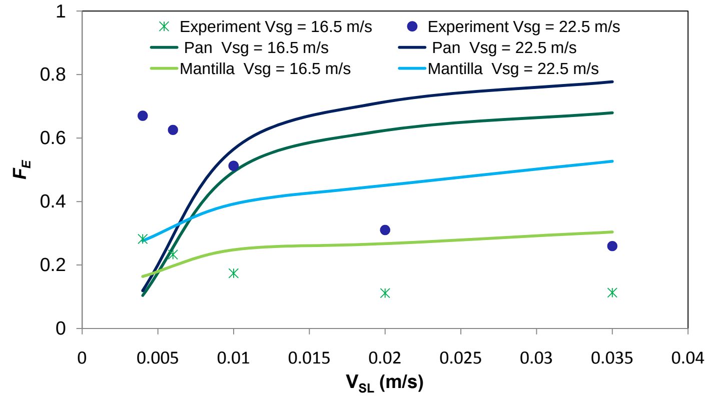
$\kappa(d_{mean},\phi)$ $\beta(d_{mean},\phi)$

Modeling …

- Droplet Transport in the Continuous Phase – Turbulent Diffusion in Horizontal Rectangular Channel
  - Convection/Diffusion Model – *Binder and Hanratty 1992*
  - Analytical Solution for Convection/Diffusion Model – *Mols and Oliemans 1998*
  - Corrections for Mols and Oliemans Solution – *Torress-Monzon 2006*

Liquid Entrainment

- Model Comparison of data For Current Study



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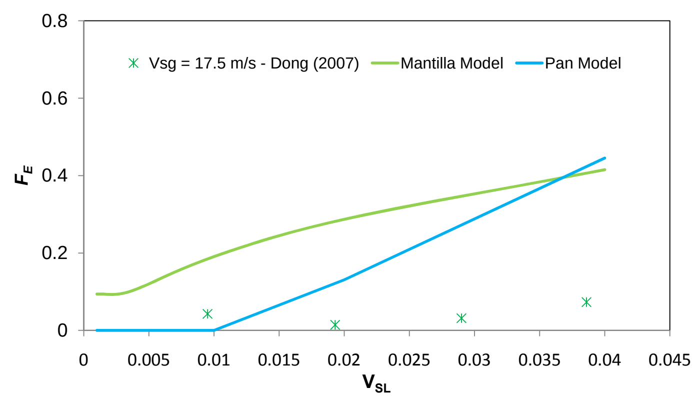
Liquid Entrainment …

- Model Comparison with Dong (2007) Data for 6-inch Pipe



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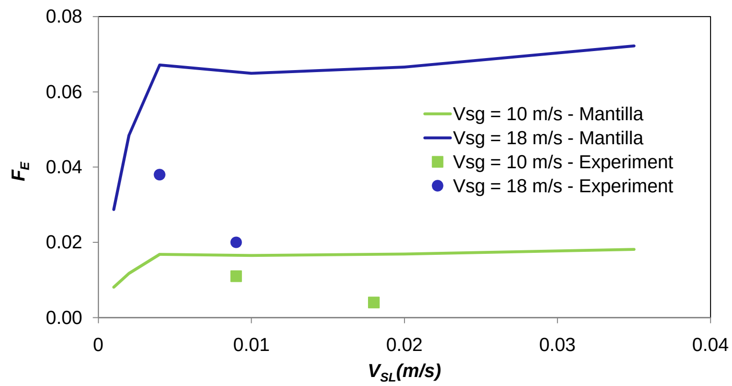
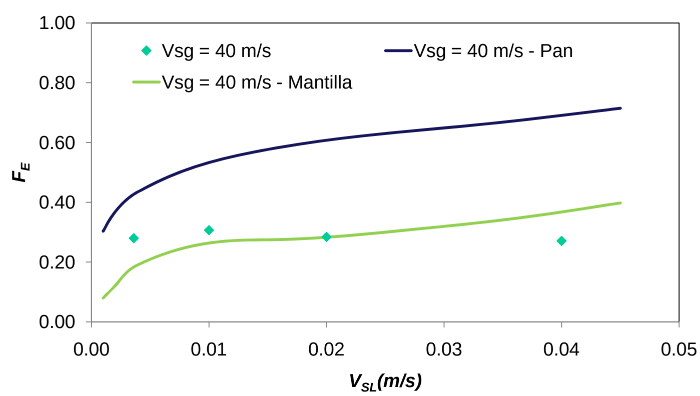
Liquid Entrainment …

- Model Comparison with Mantilla (2008) Data for 6-inch Pipe



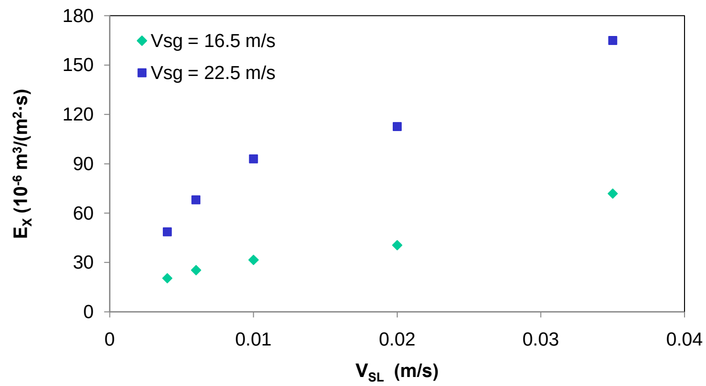
Liquid Entrainment …

- Model Comparison with Magrini (2009) Data



Liquid Entrainment …

Total Entrainment Flux



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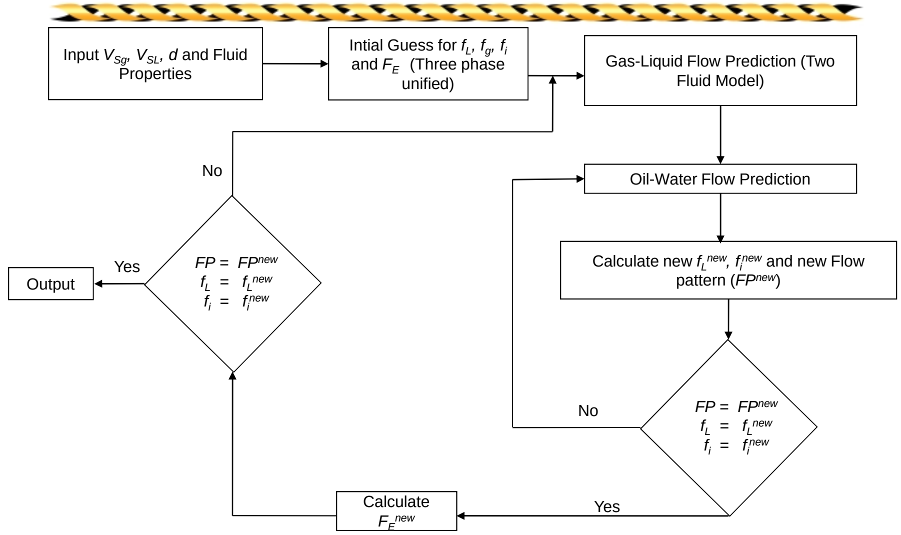
Preliminary Modeling Scheme



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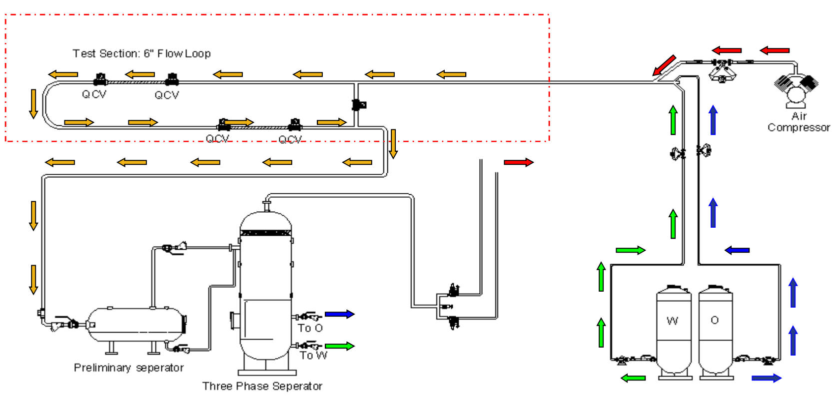
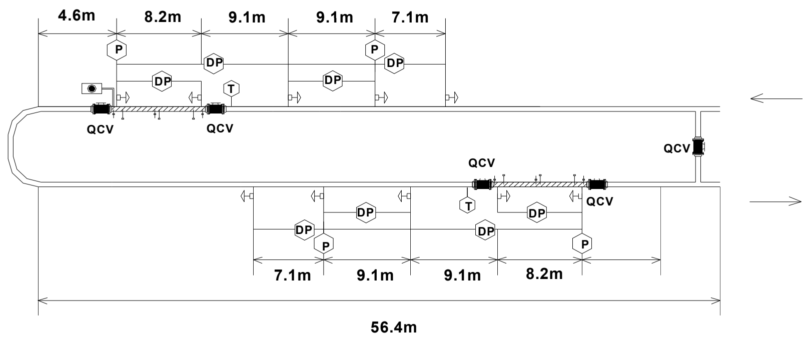
Experimental Study

- Experimental Facility
- Test Section
- Test Fluids
- Instrumentation and Data Acquisition
- Experimental Program
- Experimental Results

Facility …



Test Section



Test Fluids

- Test Fluid
  - Gas – Air
  - Water – Tap Water
  - Oil – Isopar L
- Properties Resembling Those of Wet Gas Condensate
  - Low Viscosity and Specific Gravity

Instrumentation/Data Acquisition

- Pressure and Temperature: PTs and DPs and TTs
- Holdup: Quick Closing Valves and Pigging System
- Wetted Wall Perimeter: Scales on Wall
- Liquid Film Thickness: Capacitance Probes

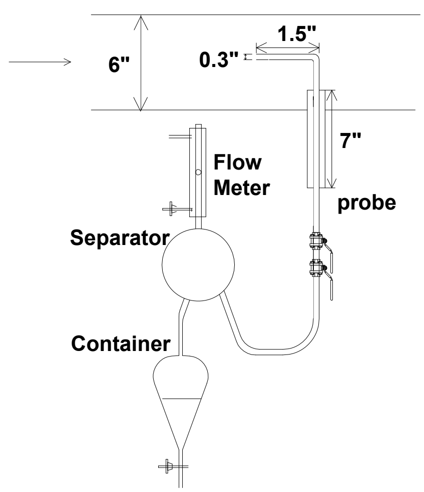
Instrumentation/Data Acquisition …

- Liquid Entrainment: Iso-kinetic Sampling System and Film Removal Device
- Fisher Scientific Semi-automatic Model 21 Surface Tensiomat
- Data Acquisition: Delta-V

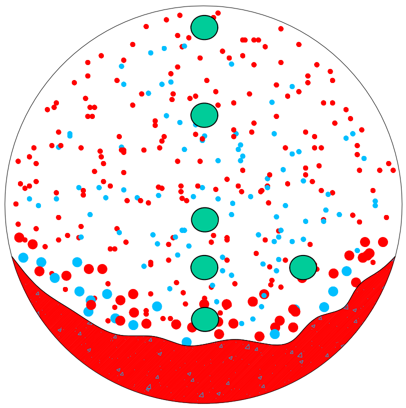
Entrainment Study

- Onset of Entrainment
- Vertical Flow – Entrainment Uniform Across Pipe
- Entrainment Profile Across Pipe Cross Section
  - Iso-kinetic Probe at Different Positions Across Pipe

Iso-kinetic Probe



Probe Locations



Fluid Flow Projects

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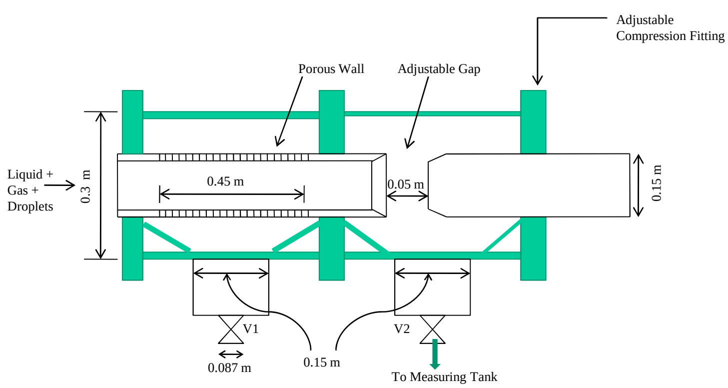
Film Removal Device



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Experimental Program

- Tests at Low Gas Flow Rates
  - Flow Conditions Used by Dong (2007)
- Tests at High Gas Flow Rates
  - Gas-Oil 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 0.5
  - Inclination Angles:
    0°, +2°, -2°

Low Gas Flow Rate Studies

- Test Matrix

Superficial Gas Velocity (m/s)	Superficial Liquid Velocity (m/s)			
	Water Cuts : 0, 5%, 10%, 20%, 50%			
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%, 10%, 20%, 50%			
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

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Near Future Tasks

Literature Review	Ongoing
Instrumentation	May 2011
Testing	Nov 2011
Data Analysis and Model Development	Feb 2012
Final Report	May 2012

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Questions

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

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	December 2011
Model Validation	February 2012
Final Report	May 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 experimetnal 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 and entrainment fractions will be observed and measured at different flow rates, liquid loading levels and water cuts.

Activities Summary

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. The instrumentation on both the runs (pressure transmitters, differential pressure transducers and temperature transmitters) has been installed and re-calibrated. Preliminary experiments were performed to check the facility and the instruments.

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. This involves measuring the entrainment flux at different positions along the pipe cross-section and integrating over the entire pipe cross-section. A film extractor has been designed to withdraw the liquid film from the pipe wall. The total entrainment fraction will be determined by subtracting the film flow rate from the total liquid flow rate.

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.

New Measurement Techniques

Detailed literature review was conducted for new measurement techniques to be considered in the current project. Droplet transport mechanism strongly depends on droplet size. Thus, any mechanistic model for entrainment fraction should account for the size of entrained droplets. A high speed imaging system is being designed for determination of size distribution of entrained droplets. The applicability of this high speed imaging system for determination of gas entrainment in the liquid phase and liquid film velocity is also being investigated. Oil/water flow pattern identification is currently done by visual inspection. A new capacitance probe is being built for this purpose since visualization is difficult especially at higher gas flow rates.

Future Work

- Complete testing for proposed test matrix.
- Ph.D. proposal defense.
- 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).

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

High Pressure – Large Diameter Multiphase Flow Loop Construction

Scott Graham and Cem Sarica

Outline

- Introduction
- Objectives
- Facility Construction

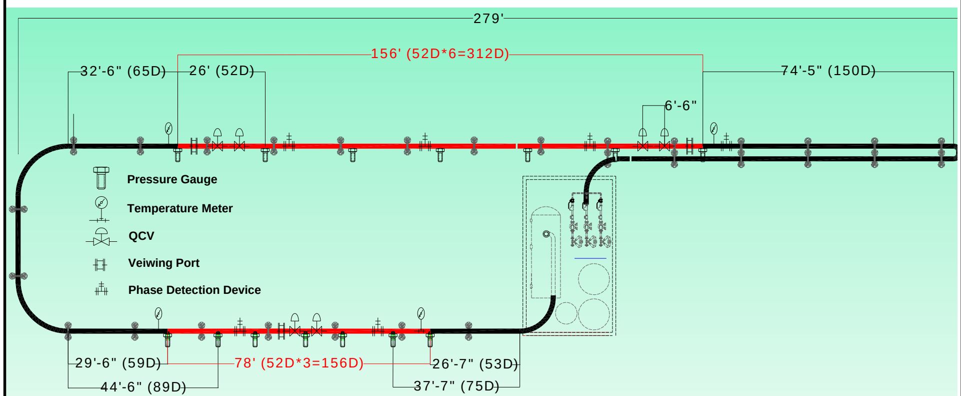
Introduction

- Pressure and Pipe Diameter Affect Flow Behavior in Multiphase Flow Significantly
- Limited Study of Multiphase Flow in Large-Diameter Pipes at Pressure Conditions Higher than 2,000 kpa (290 psi)
- Need
  - Investigation of Diameter and Pressure Effects on Multiphase Flow
  - Experimental Data
- Requires a Proper Facility

Objectives

- Design and Construct a 6 in. ID High Pressure Multiphase Facility
- Conduct Research Projects to Better Understand Multiphase Flow
- Upscale Available Predictive Tools

Facility Layout



Construction Activities

- Equipment Pad
- Piers
- Structure
- Piping
- Equipment
- Vessels

Fluid Flow Projects

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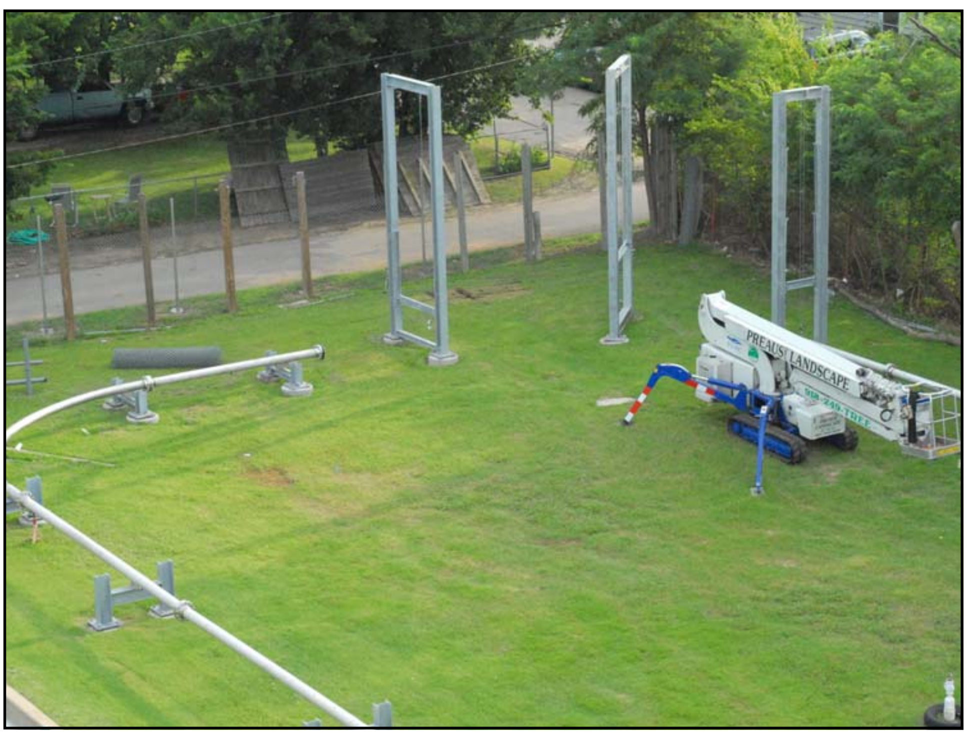
PREAUS LANDSCAPE


LANDSCAPE


PREAUS LANDSCAPE OF
ARBORISTS - LANDSCAPE CONTRACTO


BELGER
Ingersoll-Rand
Hertz


KOHLER
Allen-Bradley
Allen-Bradley


SULLAIR 1800e
Senergy

Fluid Flow Projects

Effects of Pressure on Low Liquid Loading

Mujgan Guner

Advisory Board Meeting, May 12, 2011

Outline

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

Objectives

- Acquire Experimental Data for Low Liquid Loading at High Pressure and Large Diameter
- Verify and Improve of Existing Closure Relationships and Models
- Develop an Improved Model for Low Liquid Loading at High Pressure and in Large Diameter Pipes

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Literature Review

- Low Liquid Loading Two-Phase Flow
  - Meng *et al.* (1999)
    - Air and Oil as Working Fluids
    - Low System Pressure (15 psi)
    - 180 Data Points from 2 in. ID Facility Horizontal and Near Horizontal Configuration
    - Pressure Gradient, Liquid Holdup, Wetted Wall Fraction, Liquid Entrainment and Film Thickness Data
    - Mechanistic Two-fluid Model is Developed

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Literature Review …

- Low Liquid Loading Two-Phase Flow
  - Badie *et al.* (2000)
    - Air-Oil and Air-Water as Working Fluids
    - Low Pressure 3 in. ID Facility Horizontal and Near Horizontal Configuration
    - Pressure Gradient and Liquid Holdup are Investigated
    - Comparison of ARS and Double Circle Models

Literature Review …

- Low Liquid Loading Two-Phase Flow
  - Fan *et al.* (2005)
    - Air and Water as Working Fluids
    - 167 Data Points from 2 in. ID , 184 Data Points from 6 in. ID Facilities Horizontal and Near Horizontal Configuration
    - 5< v_{SG} <25 m/s, 0.00025< v_{SL} <0.03 m/s for Small Scale
    - 7.5< v_{SG} <21 m/s, 0.005< v_{SL} <0.05 m/s for Large Scale
    - Mechanistic Two-fluid Model with New Closure Relationship is Developed

Literature Review …

- Low Liquid Loading Three-Phase Flow
  - Gawas (2010)
    - Gas-Oil-Water as Working Fluids
    - Low Pressure (15 psi) 6 in. ID Facility Horizontal and Near Horizontal Configuration
    - Pressure Gradient, Liquid Holdup, Wetted Wall Fraction, Liquid Entrainment, Flow Patterns and Film Thickness are Investigated

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Literature Review …

- Low Liquid Loading Two-Phase Flow
  - Kjolaas *et al.* (2011)
    - Nitrogen and Naphta as Working Fluids
    - High Pressure (1300 psi) 8 in. ID Facility Near Horizontal Configuration
    - Velocity Profiles, Flux and Liquid Entrainment are Investigated

Fluid Flow Projects

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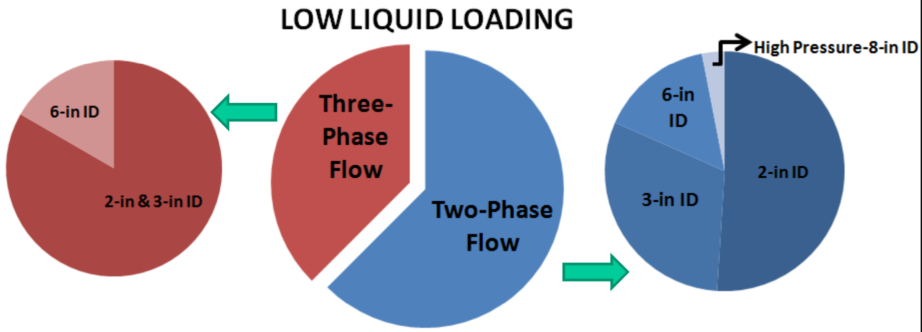
Literature Review …



- Lack of High Pressure Large Diameter Low Liquid Loading Studies

Proposed Study

- Experimental and Modeling Study of Pressure Effects on Low Liquid Loading Two-phase Flow in Horizontal Pipes
- Experimental Study will be Conducted in Newly Constructed 6 in. ID High Pressure Facility

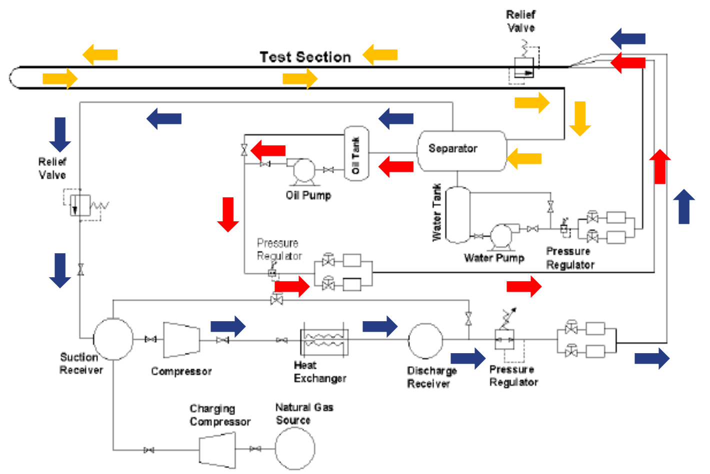
Proposed Study …

- Parameters to Investigate
  - Pressure Gradient
  - Liquid Holdup
  - Liquid Entrainment
  - Wave Characteristics
- Experimental Data will be Used to Verify and Improve Existing Closure Relationships and Mechanistic Models or Develop New Ones If Necessary

Facility

- Piping and Structure Constructions are Completed
- Electrical Systems, Data Acquisition, Control Systems and Instrumentation are Under Construction
- Anticipated Date for Facility Commissioning is June 1
- HAZOP Study is Needed

Facility …



Fluid Flow Projects

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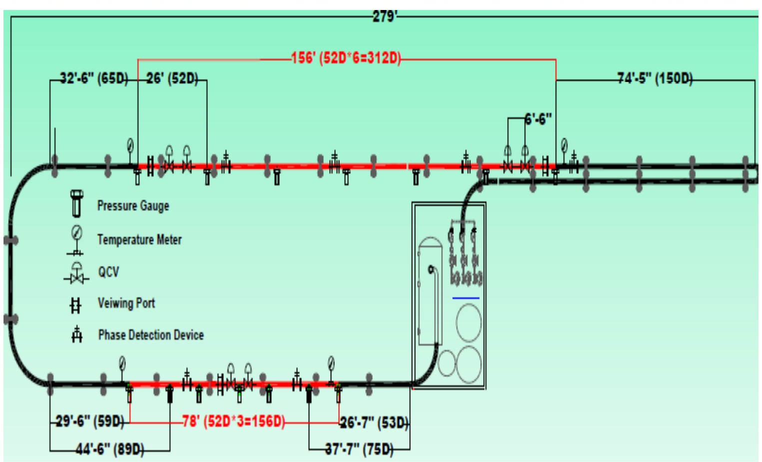
Facility …



Fluid Flow Projects

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Test Fluids

- Test Fluid
  - Nitrogen – Oil
- Nitrogen is Selected as Gas Phase
- Oil Resembling Wet Gas Condensate is Selected
  - Isopar L
- Surface Tension Effects will be Studied with the Addition of Surfactants
  - Surfactant Removal Needs to be Addressed

Instrumentation / Basic

	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

Instrumentation / Special

- Liquid Holdup
  - Gamma Ray Densitometer
  - Quick Closing Valves
- Liquid Entrainment
  - Isokinetic Sampling Device
  - Laser Doppler Anemometry

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Instrumentation / Special …

- Wave Characteristics
  - Capacitance Sensor
- Visual Observation
  - Transparent Window
  - Sapphire Pipe for Boroscope
  - EnviroCam Boroscope Equipped with Sapphire Tip
    - TUHOP Will Utilize it in 3 in. ID Loop

Fluid Flow Projects

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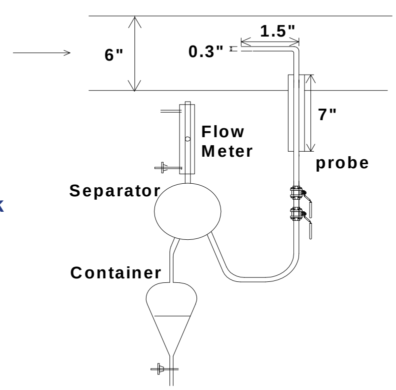
Instrumentation / Special …

- Gamma Ray Densitometer
  - Single-Beam Gamma Densitometer
    - Gives Accurate Information in Homogenized Flows
  - Broad-Beam Gamma Densitometer
  - Multi-Beam Gamma Densitometer
    - More Accurate Results in Stratified Flow, Slug Flow and Annular Flow

Instrumentation / Special …

- Isokinetic Sampling
  - Utilized Recently in SINTEF High Pressure Large Diameter Facility
  - Differences from Low Pressure System
    - Pressurized Collection Tank
    - Return System for Gas
    - Control System to Ensure Isokinetic Conditions
    - Proper Flow Meter for Application
    - Proper Sealing



Instrumentation / Special …

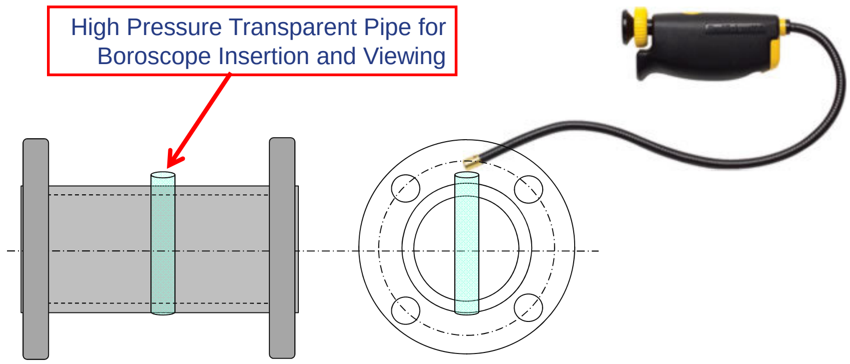
- Laser Doppler Anemometry (LDA)
  - Non-intrusive Measurement Technique for Local Velocities of Droplets in Gas or Bubbles in Liquid
  - High Degree of Spatial Resolution and Fast Data Acquisition
  - Requires Transparent Section
  - Utilized Recently in SINTEF High Pressure Large Diameter Facility

Instrumentation / Special …

- Visual Observation
  - Block Section
    - Acrylic
      - Safety Concern
    - Lexan
      - Visibility Concern
    - Sapphire
      - Cannot Grow in 6 in. ID Size
  - Sapphire Windows
    - Embedded in Steel
    - Multiple Locations

Instrumentation / Special …

- Visual Observation …
  - Boroscope



Fluid Flow Projects

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Instrumentation / Special …

- EnviroCam System
  - In-situ Vision Analysis System
  - Allows Remote Observation, Verification, Recording, and Analysis in Real Time
  - Can be Operated at High Pressures
  - TUHOP Will First Test It in a 3 in. ID Flow Loop

Fluid Flow Projects

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Near Future Tasks

- Literature Review — Ongoing
- Facility Commissioning — June 2011
- Ph.D. Qualifying Exams — Aug. 2011
- Instrumentation — Fall 2011

Questions & Comments

Fluid Flow Projects
Advisory Board Meeting, May 12, 2011

Effects of Pressure on Low Liquid Loading

Mujgan Guner

Project Completion Dates

Objectives

The three main objectives of this study are:

- Acquire experimental data for low liquid loading two-phase flow in a 6-in. ID pipe at elevated pressures;
- Verify existing closure relationships and models;
- Improve existing models or develop new ones if needed.

Introduction

Low liquid loading is a widely encountered phenomenon in wet gas transmission pipelines. Understanding of low liquid loading is essential to proper pipeline and downstream facilities design and management of chemicals used for flow assurance purposes such as corrosion inhibitors.

Several studies address the experimentation and modeling of two phase low liquid loading. However, they are typically limited to flow in small diameter pipes for low pressure conditions. In this study, low liquid loading gas-oil flow experiments will be conducted in a newly constructed 6-in. ID high pressure flow loop.

Activities Summary

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

Literature Review

For low pressure systems (less than 30 psi), Meng *et al*. (1999) studied oil-air low liquid loading flow in horizontal and near horizontal 2-in. ID pipe. They mainly focused on pressure gradient, liquid holdup, wetted wall friction factor, liquid entrainment, and film thickness. A mechanistic two fluid model based on interfacial interaction between the gas and liquid phase was proposed. Later, Badie *et al.* (2000) carried out an experimental program for low liquid loading in 3-in. ID pipes. They utilized air-oil and air-water as working fluids to measure pressure gradient and holdup. Consequently, Fan *et al* (2005) studied low liquid loading in 2-in. and 6-in. ID pipes for horizontal and near horizontal configurations. Pressure gradient, liquid holdup, wetted wall fraction, liquid entrainment and film thickness were investigated. Models and closure relationship for wetted wall fraction, liquid wall fraction, and interfacial friction factor were proposed.

Currently, Gawas (2010) is conducting an experimental study in low liquid loading for gas-oil-water three-phase flow using a 6-in. ID flow loop for horizontal and near horizontal configurations at low pressures. He is investigating pressure gradient, liquid holdup, wetted perimeter, liquid entrainment, flow patterns and wave characteristics. Kjolass *et al*. (2011) performed experiments in an 8-in ID pipe to investigate detailed flux and velocity profiles in two-phase low liquid loading with Nitrogen and Naphta at high pressure (1300 psi).

The literature review reveals a lack of experimental and theoretical studies for low liquid loading at high pressure and large pipe diameters. Additionally, pressure effect on low liquid loading is still not well understood and experimental investigation is required to improve the actual models prediction.

Experimental Facility

The experimental facility for this study is the newly constructed 6-in. ID flow loop. The maximum operating pressure is 500 psig. Maximum superficial liquid and gas velocities are 0.7 m/s and 10 m/s, respectively. The test section of the facility consists of two parts. The first part or Part-1 is 156 ft long (312 D) and adjustable to inclination angles (-3° to 3°). The second part or Part-2 is 78 ft long and horizontal.

Test Fluids

The main objective of the low liquid loading is to simulate the flow phenomena in wet gas transmission pipelines. Therefore, the selected oil should resemble the gas condensates, which have low viscosity and low specific gravity. The oil is selected as Isopar L. Initially, Nitrogen is selected as a gas phase, due to safety issues.

Surface tension is also another parameter to be investigated. Surfactants may be added to the selected oil to modify the surface tension without affecting the other fluid properties considerably.

Experimental Program

Experiments will be conducted for oil-gas two-phase flow and horizontal configuration. The main parameters to be investigated are pressure gradient, liquid holdup, liquid entrainment, and wave characteristics at an elevated pressure (500 psi).

Instrumentation and Data Acquisition

The DeltaV™ digital data automation system is used as the data acquisition software.

Pressure, temperature and pressure gradients will be measured using Rosemount pressure, temperature and differential transducers.

Quick closing valves will be utilized for liquid holdup measurements. Moreover, gamma ray densitometer is considered for holdup measurements. There are three types of gamma ray densitometers; single-beam, broad-beam, and multi-beam. The single-beam gamma ray densitometer does not give accurate results in segregated flows such as stratified flow, slug flow and annular flow. Therefore, broad-beam or multi-beam gamma ray densitometers are better alternatives to use.

Isokinetic sampling is considered for liquid entrainment measurements. Recently, Kjolass *et al.* (2011) utilized isokinetic sampling technique for high pressure systems. Moreover, they used Laser Doppler Anemometer (LDA) to measure the liquid droplet and gas bubbles velocities in stratified flow. Base on this application, LDA is being considered as a potential instrumentation for this study.

Visual observations are needed for flow pattern observations and possibly pre-requisite for other instruments such as LDA. For visual observations, two configurations can be implemented in the high pressure loop. The first one is a visual window with a fully sealed section. The second configuration is a vertical sapphire pipe insert and a traversable boroscope assembly. Another boroscope system designed by EnviroCam will be considered to use in the facility. It is an in-situ vision analysis system, therefore does not require a sapphire tube. EnviroCam can be operated in high pressure applications and allows remote observation, verification, recording and analysis in real time. TUHOP will first test in a 3-in ID flow loop.

Modeling Study

Experimental data will be used to verify and improve existing closure relationships and mechanistic models. If necessary, new closure relationships will be developed at high pressure and large diameter conditions.

Near Future Tasks

The future tasks for the next period are listed below:

- Literature review
- Ph.D. qualifying exams
- Determination of instrumentation
- Preliminary tests

References

Badie, S., Hale C. P., Lawrence, C. J., and Hewitt G. F.: “Pressure Gradient and Holdup in Horizontal Two-Phase Gas-Liquid Flows with Low Liquid Loading,” *Int. J. Multiphase Flow*, Vol. 26, No. 9, pp. 1525-1543 (2000).

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

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Meng, W.: “Low Liquid Loading Gas-Liquid Two Phase Flow in Near Horizontal Pipes,” PhD Dissertation, U. Tulsa, Tulsa, OK (1999).

Falcone, G., Hewitt. G. F., Alimonti. C.,: "Multiphase Flow Metering, Principles and Applications," Elsevier (2010).

Gawas, K.: "Low Liquid Loading Gas-Oil-Water in Pipe Flow," TUFFP ABM Nov. 12. pp. 301-313. (2010)

Fluid Flow Projects

Liquid Unloading from Gas Wells

Ge (Max) Yuan

Advisory Board Meeting, May 12, 2011

Comments from Last ABM

- Mr. Rob Sutton, Marathon
  - Comment 1: Inclination Angle Changed to Well Deviation
  - **Response 1: Accepted**
  - Comment 2: Well Deviation Range to be Narrowed to Find Maximum Critical Gas Velocity
  - **Response 2: Accepted**
  - Comment 3: Read Reference, Salim *et al.* (2009) SPE 124195
  - **Response 3:**
    - Read
    - Experimental Results
    - Drift Flux Approach to Calculate Critical Velocity

Fluid Flow Projects   Advisory Board Meeting, May 12, 2011

Comments from Last ABM …

- Dr. Jiyong Cai, ExxonMobil
  - Literature Search of
    - Film Dryout
    - Heat Transfer Coefficient in Multiphase Flow
    - Water Wall in Boiler
  - Response:
    - Investigated
    - Mainly Related to Intensive Heat Transfer
    - No Promising Studies

Comments from Last ABM …

- Mr. Luis Gutierrez, BP
  - Red Eye System to Measure the Liquid Film Velocity
  - Response:
    - Investigated
    - Red Eye System is A Multiphase Water-cut Meter
    - Not Applicable

Comments from Last ABM …

- Dr. Thomas Danielson, ConocoPhillips
  - Overall v_{SL} to Obtain Slip Velocity and Liquid Holdup
  - Response:
    - Investigated
    - Another Perspective to Looking at Liquid Loading
    - Salim *et al.* (2009) Utilized Similar Approach

Outline

- Objectives
- Literature Review
- Experimental Study
- Instrumentation
- Near Future Tasks
- Project Schedule

Objectives

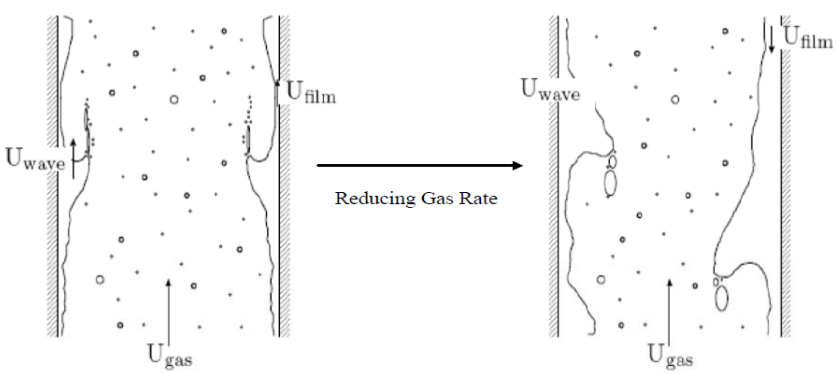
- Explore Mechanisms Controlling Onset of Liquid Loading
- Investigate Effect of Well Deviation on Liquid Loading

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Literature Review

- Liquid Film Flow Reversal



Multiphase Flow Behavior (Van ‘t Westende (2008))

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Literature Review …

- Turner's Continuous Film Model
  - Solving Liquid Film Velocity Profile

$$\frac{\tau}{\tau_0} = 1 + \frac{y\rho_L g}{\tau_0 g_c}$$

Applying Eddy Viscosity Equation, then Integration

Transition Criterion:

$$\tau_i \approx \frac{h\rho_L g}{g_c} \qquad \tau_0 \approx 0$$

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Literature Review …

- Barnea's Model
  - Transition from Slug to Annular
    - Film Instability Criterion $\frac{\partial \tau_I}{\partial \tilde{\delta}_L} = 0$

$$g(\rho_L - \rho_G) d \sin\theta [(1-2\tilde{\delta}_L)^2 - 2(\tilde{\delta}_L - \tilde{\delta}_L^{\,2})]$$

$$-\frac{1}{16} C_L \rho_L (\frac{\rho_L d}{\mu_L})^{-n} (v_{SL})^{2-n} [\frac{(\tilde{\delta}_L - \tilde{\delta}_L^{\,2}) + (1-2\tilde{\delta}_L)^2}{(\tilde{\delta}_L - \tilde{\delta}_L^{\,2})^3}] = 0$$

- Spontaneous Blockage Owing to Wave-Growth Criterion

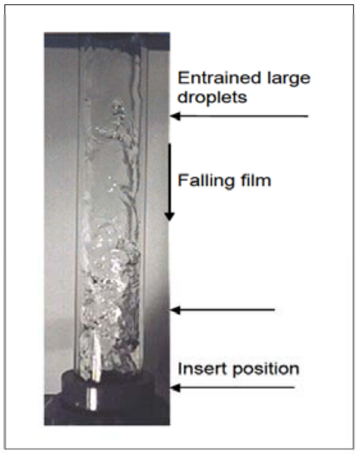
$$H_L \geq 0.24, or\, \tilde{\delta} \geq 0.065$$

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

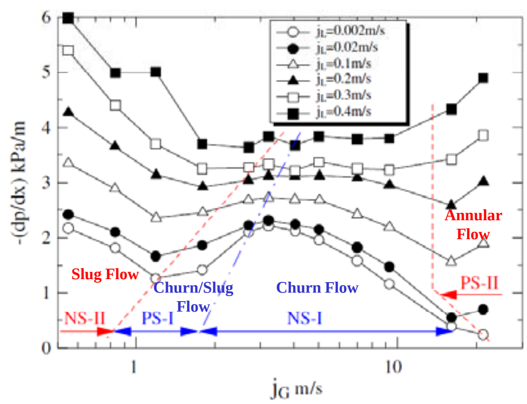
Literature Review …

First Picture of Falling Film in Literature



Multiphase flow behavior with 16 mm orifice.
(Veeken *et al.* (2010),SPE 134483)

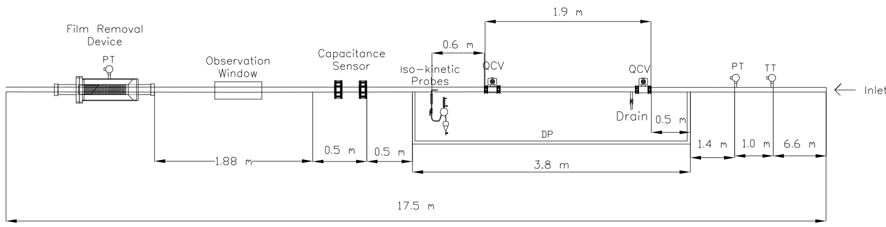
Literature Review …



Variation of Pressure Gradient with j_G (T. Sawai *et al.* (2004))
where j_G is gas volumetric flux, m/s
j_L is liquid volumetric flux, m/s

Experimental Study

- **Test Section Design**



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

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Experimental Study

- **3 inch Multiphase Flow Loop**

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Experimental Study …

➢ **Test Matrix**

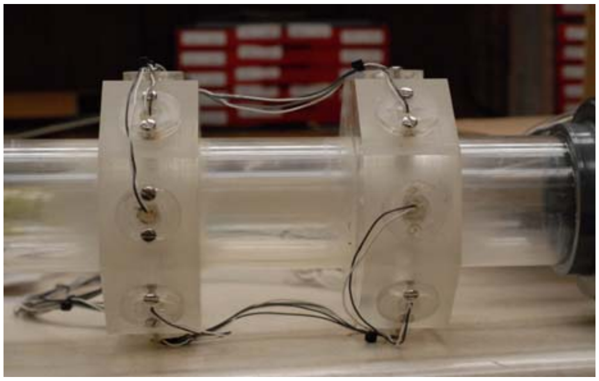
v_{SG} (m/s)	v_{SL} (m/s) Well Deviation: 0°, 25°, 30°, 45°, 60°				
10	0.005	0.01	0.02	0.05	0.1
15	0.005	0.01	0.02	0.05	0.1
20	0.005	0.01	0.02	0.05	0.1
25	0.005	0.01	0.02	0.05	0.1
30	0.005	0.01	0.02	0.05	0.1

Instrumentation

- Pressure and Temperature: PTs and DPs and TTs
- Holdup: Quick Closing Valves
- Liquid Film Thickness
- Liquid Film Flow Direction
- Liquid Film Velocity
- Liquid Entrainment Fraction (Optional)

Film Thickness: Capacitance Sensor

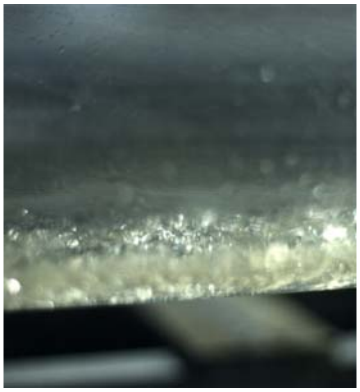
- Type: Two Parallel Wires
- Range: 0 – 20 mm



Film Flow Direction

- High Speed Camera

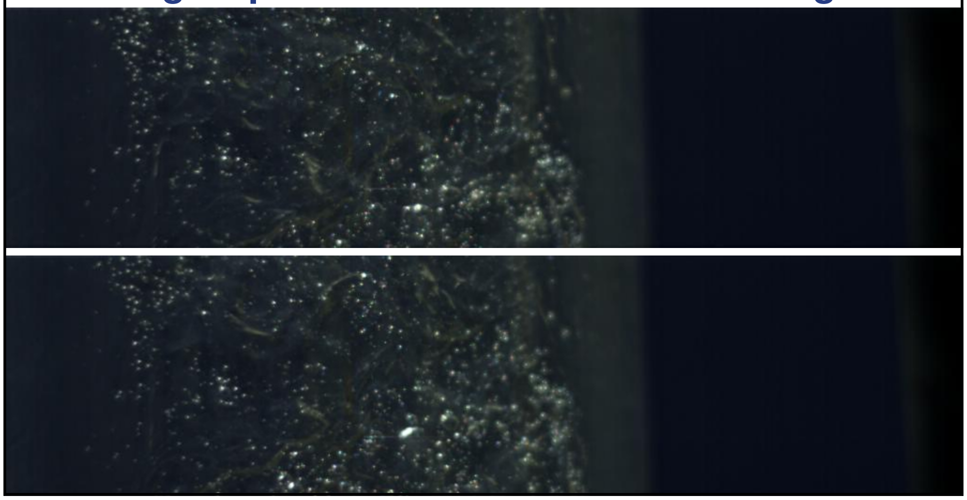
Video 1



Video 2

Film Velocity

- High Speed Camera: Bubble Tracking



Near Future Tasks

- Preliminary Testing
- Experimental Testing
- Data Analysis

Project Schedule

Literature Review	Ongoing
Facility Modification	Completed
Preliminary Testing	May 2011
Experimental Testing	August 2011
Data Analysis	September 2011
Model Comparison	October 2011
Final Report	November 2011

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Questions/Comments

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Liquid Unloading from Gas Wells

Ge (Max) Yuan

Project Completion Dates

Literature Review	Ongoing
Facility Modification	May 2011
Preliminary Testing	May 2011
Experimental Testing	August 2011
Data Analysis	September 2011
Model Comparison	October 2011
Final Report	November 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.

Activities Summary

A summary of the most relevant activities during this reporting period is presented in this section:

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 so-called Turner expression for liquid loading includes a 20% upward adjustment to best-fit field data. The Turner method has been widely used in the industry for decades because it only requires 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. In the lower zone, the liquid film is thick, and its direction of flow is varying 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) has been modified for this project. The facility is capable of being inclined from horizontal to vertical. Pressure and temperature transducers are placed near the test section to obtain fluid properties and other flowing characteristics. Compressed air and Tulsa city tap water will be used in this study.

Instrumentation and Data Acquisition

The test section of the facility has been modified to accommodate the needs of this study. Capacitance sensors will be used for the liquid film thickness measurement. The sensor is a two parallel wire sensor with a capacity of measuring maximum film thickness of 20 mm. The configuration of the four probes are placed at the bottom, at the top, at the right and left sides of the circumference of the pipe. High speed camera is used to record the liquid loading phenomena. Preliminary testing of the high speed camera has been completed. When the shutter speed is increased to 100,000 per second, lights from the environment are blocked out even without observation windows, which make the background of the images dark. Bubbles entrained in the liquid film can be identified from the images. Wave propagation was also observed from the video. From the videos and images taken, the flow direction of liquid film as well as film velocity can be. A commercial image processing software named Image Probe will be used.

Experimental Program

In this study, experiments will be conducted at different flow conditions in terms of flow rates and inclination angle. Superficial water velocities range from 0.005 to 0.1 m/s. Superficial gas velocities range from 10 to 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. Film flow direction and film velocity are of great importance in this project. During one test run, liquid flow rate will be constant and gas flow rates will be decreased step by step until liquid loading happens. The onset of liquid loading is defined as the liquid film flowing downward while the gas core is still flowing upward.

Near Future Tasks

Experimental Testing – August 2011

Experiments will be conducted according to the testing matrix. After these are finished, the well deviation range will be narrowed to probably 70° to 50° to find the maximum critical gas velocity.

Data Analysis – September 2011

Film thickness and wave characteristics will be obtained from the capacitance sensor data. Film velocity will be obtained from the images taken by high speed camera system. Onset of liquid loading will be defined. Critical velocity will be identified for each test.

Model Comparison – October 2011

Test results will be compared with predictions by different models, such as Turner's model, TUFFP Unified Model, Barnea's model and OLGA simulation.

Final Report – November 2011

Final report will be submitted, and thesis will be defended.

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

Simplified Transient Two-Phase Flow Modeling

Jinho Choi

Outline

- Objectives
- Past Activities
- Current Activities
  - Simplified Drift Flux Model
  - Simulator Structure
- Near 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

Past Activities

- Previous TUFFP Transient Model
  - Combination of Two-fluid Model and Drift Flux Model
  - Each Model Gave Good Predictions for Different Flow Patterns
  - Flow Pattern Prediction was Required to Determine the Model to Use
  - Not Incorporated PVT Table and Heat Transfer Model
  - Need to Develop Simpler Model for Every Flow Pattern

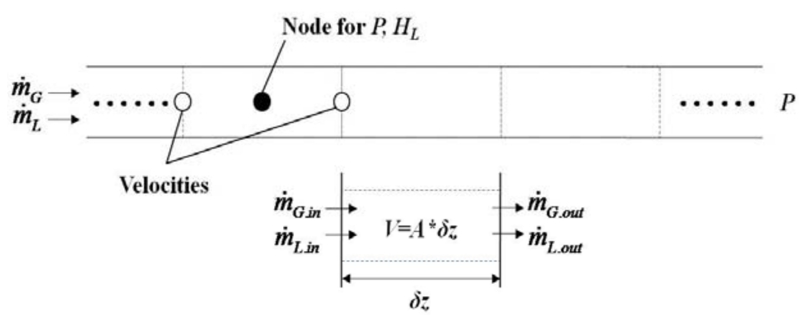
Current Activities

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

Fluid Flow Projects

Simplified Drift Flux Model

- Control Volume and Boundary Conditions



Fluid Flow Projects

Simplified Drift Flux Model

Control Volume and Boundary Conditions

❖**Input Variables**

➢**Boundary Values**

- $\dot{m}_L$ → Liquid Flow Rate
- $\dot{m}_G$ → Gas Flow Rate
- P_{SEP} → Outlet Pressure

➢**Geometries**

- A → Cross Sectional Area
- δz → Segment Length
- θ → Inclination Angle

$\dot{m}_{L.in}$ $\dot{m}_{G.in}$

$\dot{m}_{L.out}$ $\dot{m}_{G.out}$

P_{in} P_{out}

dP/dL

Fluid Properties

❖**Output Variables**

For Each Segments

- P → Pressure
- H_L → Liquid Holdup

Simplified Drift Flux Model

Liquid Continuity

$$\frac{dm_L}{dt} = \dot{m}_{L.in} - \dot{m}_{L.out}$$

❖**Assumption**

➢ Constant Liquid Density

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

Gas Continuity

$$\frac{dm_G}{dt} = \dot{m}_{G.in} - \dot{m}_{G.out}$$

$$\rightarrow \frac{d[\rho_G(1-H_L)]}{dt} = \frac{\rho_G(u_{SG.in} - u_{SG.out})}{\delta z}$$

Simplified Drift Flux Model

- **Combined Continuity**

$$-\rho_G\left[\frac{u_{SL.in}-u_{SL.out}}{\delta z}\right]+(1-H_L)\left[\frac{\partial\rho_G}{\partial P}\frac{dP}{dt}+\frac{\partial\rho_G}{\partial T}\frac{dT}{dt}\right]=\rho_G\left[\frac{u_{SG.in}-u_{SG.out}}{\delta z}\right]$$

Assumptions

- Isothermal Flow
- Constant Gas density

$$\longrightarrow \boxed{u_{SL.in}-u_{SL.out}+u_{SG.in}-u_{SG.out}=0}$$

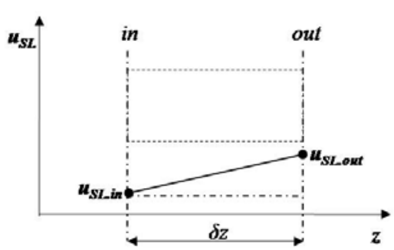
Simplified Drift Flux Model

- **Drift Flux Closure Relationship**

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

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

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



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

Simplified Drift Flux Model

Drift Flux Model

- Application of the Combined Continuity

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

- Explicit Solutions

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

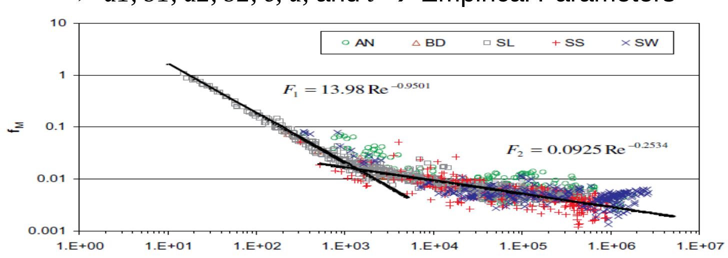
$$u_{SL.out}=u_{SG.in}+u_{SL.in}-u_{SG.out}$$

Simplified Drift Flux Model

Pressure Gradient

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

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



* Garcia *et al.*, "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(2003), 1605-1624, 2003

Simplified Drift Flux 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 Structure

Main

Read Input Data
- Pipeline Profile
- Boundary Conditions
- Fluid Properties

Numerical Simulation

Initialization
- Steady-State Assumption
- Gas Properties → *f*(*Pressure*)
- Iteration for Pressure

Solver
- Calculate Flow Rates of Every Segments from Inlet BC
- Calculate Pressures of Every Segments from Outlet BC
- Gas Properties → *f*(*Pressure*)
- Iteration for Pressure

→ ***Matrix Solution***

Output Data

Selected Segment, Whole Time Steps
- Pressure
- Liquid Holdup

Near Future Work

- Preliminary Code Validation and Debugging (May, 2011)
- Properties Determination from Lookup Table Produced by PVTSim (June, 2011)
- Inclusion of Heat Transfer Model (July, 2011)
- Extension of Drift Flux Model to Segregated Flow Patterns (July, 2011)
- Implicit Scheme Implementation (August, 2011)
- Test of Model and Simulator (October, 2011)

Questions and Comments

?

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Simplified Transient Gas-Liquid Two-Phase Flow Modeling

Jinho Choi

Project Completion Dates

Objective

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 provided good prediction for stratified flow, while drift flux model was more suitable 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 based on the extension of drift flux model for all flow patterns. As a starting point, Danielson and Fan (2010) drift flux model was adopted.

Activities Summary

During this period, a simplified isothermal drift flux model has been developed as a preliminary model. Simulator design, code and validation are ongoing.

Drift Flux Model

Control Volume and Boundary Condition

Inlet gas and liquid flow rates of the very first segment and outlet pressure of the very last segment are given as boundary conditions. A pipeline is divided into segments. Each segment has geometric properties like cross-sectional area, segment length, roughness, and inclination angle. Gas and liquid flow rates are calculated at inlet and outlet boundaries of each segment, while the pressure and holdup are given at the center of the element. Densities and viscosities are calculated using arithmetic mean average pressures of each segment. Initially, isothermal flow is assumed.

Continuities

Applying liquid continuity in each segment, the rate of change of liquid holdup with time is defined assuming incompressible liquid. On the other hand, for gas continuity, the gas density is function of pressure and temperature. After combining the gas and liquid continuities with the assumption of constant pressure and temperature in a segment, a simple mixture continuity equation is obtained. The outcome is that the summation of inlet and outlet gas and liquid superficial velocities for each segment is zero.

Mixture Momentum (Pressure Gradient)

Mixture density and velocity are required to calculate pressure gradients, which can be divided into frictional and gravitational pressure gradient. Garcia *et al.* (2003) composite friction factor is suggested for frictional pressure drop calculation. This approach is simple, accurate and flow pattern independent, which are the desired characteristics of the proposed applications.

Drift Flux Closure Relationship

In the drift flux model, a gas velocity can be calculated by the combination of a mixture velocity and a drift velocity. Equations for outlet gas and liquid superficial velocities are derived as explicit solutions using gas velocity equation and combined continuity equation.

Simulator Structure and Preliminary Coding

A simulator structure has been proposed before the preliminary code implementation. The main program of simulator consists of three components. The first is the input data, followed by the numerical simulation, and finally the output or post-processing module. Data input component reads input values like 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 modules. Based on the input data, the initialization module makes initial conditions for whole pipelines assuming steady state. Numerical solver calculates changes of variables like flow rates, pressures, and liquid holdups with time.

The programming language is selected as Fortran. Data input and output components and initialization part of numerical simulation component are completed for preliminary code. Numerical solver part will include matrix solver for calculation. Currently, the solution matrix is being generated.

Future Work

The preliminary code will be validated with previous TUFFP transient model, OLGA, and Vigneron *et al.* (1995) experimental data.

After an extensive debugging process, the inclusion of lookup table for fluid properties will be implemented. PVTSim file format as used by OLGA is suggested as fluid properties table format.

A better the drift flux closure relationship for segregated flow patterns is required to improve the accuracy of the simulator. Danielson and Fan (2010) approach will be considered for this extension.

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).

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).

Fluid Flow Projects

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

Wei Zheng

Advisory Board Meeting, May 12, 2011

Outline

- Objective
- Introduction
- Literature Review
- Modeling Approaches
- Project Schedule

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
- Applications
  - Wax Deposition
  - Hydrate Formation
  - Heavy Oil Flow
  - …

Literature Review

- Single-Phase Correlations
  - Fully Developed Laminar Liquid Flow
    - Sieder-Tate (1936)
    - Shah and London (1978)
  - Fully Developed Turbulent Liquid Flow
    - Petukhov-Kirillov (1970)
  - Fully Developed Turbulent Gas Flow
    - Dittus-Boulter (1930)

Literature Review …

- Single-Phase Approach Used for Multiphase Flow Heat Transfer Calculations
  - OLGA
  - PIPEsim
- Mixture Physical Properties Required

Literature Review …

- Bubbly Flow
  - Aggour (1978)
- Intermittent Flow
  - Rezkallah-Sims (1987)
- Annular Flow
  - Ravipudi-Godbold (1978)

Literature Review …

- Manabe *et al*. (2003)
  - Two-Phase Vertical Flow
  - Flow Pattern and Hydrodynamics Prediction: Ansari *et al.* (1994)
  - Average Convective Heat Transfer Coefficients for Different Flow Patterns

Literature Review …

- Manabe *et al*. (2003)
  - Bubbly Flow
    - Liquid Physical Properties Utilized
  - Annular Flow

$$\frac{h_{TP}}{h_{SF}} = 2.08 H_{LF}^{-2/3}$$

  - Intermittent Flow

$$h_{TP} = h_{TB}\beta + h_{LS}(1-\beta)$$

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Literature Review …

- Kim *et al*. (2005)
  - Horizontal Pipe Flow
  - Flow Pattern Factor F_P (Effective Wetted-Perimeter) Introduced

$$h_{TP} = F_p h_L \left\{ 1 + 0.7 \left[\left(\frac{x}{1-x}\right)^{0.08} \left(\frac{1-F_p}{F_P}\right)^{0.06} \left(\frac{Pr_G}{Pr_L}\right)^{0.03} \left(\frac{\mu_G}{\mu_L}\right)^{(-0.14)} \right] \right\}$$

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Literature Review …

- Zhang *et al*. (2005)
  - All Inclinations
  - Flow Pattern and Hydrodynamics Predictions from Unified Hydrodynamic Model

Literature Review …

- Zhang *et al*. (2005)
  - Bubbly Flow
    - Pseudo Single-Phase
    - Fluid Physical Properties Estimated Based on H_L

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

Literature Review …

- Zhang *et al*. (2005)
  - Stratified/Annular Flow
    - Heat Loss across Liquid-Film Equals Heat Exchange with Gas Core and Surroundings

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

Literature Review …

- Zhang *et al*. (2005)
  - Slug Unit
    - Film Region
    - Slug Region

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

Literature Summary

- Models Evolved from Correlation to Mechanistic Approach
- Improved Uncertainty of Gas/Liquid Heat Transfer Model
- No Mechanistic Heat Transfer Model for Gas/Oil/Water Pipe Flow Found

Gas/Oil/Water Pipe Flow Heat Transfer Modeling

- 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

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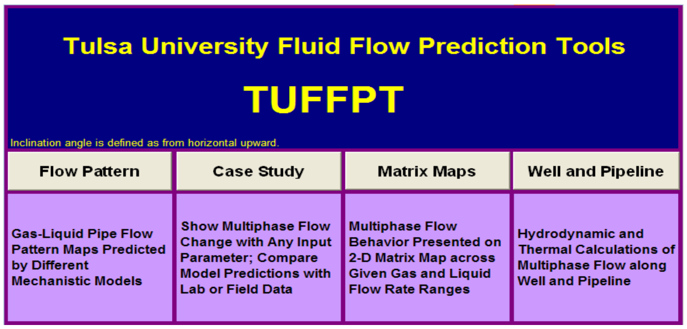
Gas/Oil/Water Pipe Flow Heat Transfer Modeling …

- Add Heat Transfer to TUFFPT Three-Phase Flow Calculation Based on Hydrodynamic Outputs from Unified Model



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Gas/Oil/Water Pipe Flow Heat Transfer Modeling …

- Second Approach
  - TUFFP Three-Phase Unified Model Will be Used for Hydrodynamic Calculations
  - Derive Overall Convective Heat Transfer Coefficient Based on Heat Balance Equations of Different Phases and Different Flow Patterns

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Model Evaluation

- Compare with Manabe's (2001) Experimental Results
- Literature Review is Underway, More Experimental Data May Be Found

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Project Schedule

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

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Questions/Comments

?

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

Wei Zheng

Project Completion Dates

Literature Review .... Ongoing
Modeling – 1st Approach .... August 2011
Modeling – 2nd Approach .... February 2012
Model Evaluation .... March 2012
Software Implementation .... May 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 -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. Wax deposition and hydrate formation are all thermal driven processes. Temperature also has a significant effect on oil viscosity, which is one of the most important parameters to characterize the flow behavior.

Single-phase heat transfer in pipelines has been widely studied and well understood, while the multiphase flow heat transfer is still under investigation. Comparing to single-phase, multiphase flow has complex flow patterns and requires more sophisticated fluid flow description for heat transfer characterization.

Activities Summary

Available single-phase and two-phase heat transfer models have been reviewed.

Single-Phase Heat Transfer Models

Over-all heat transfer coefficient is a serial combination of thermal convection inside the pipe, heat conduction through the pipe wall and insulation and heat transfer outside the pipe. The inside convection heat transfer coefficient is dependent on the hydrodynamics of the pipe flow. For single-phase heat transfer, most widely used correlations for convection heat transfer coefficient are chosen from the literature. Sieder-Tate (1936) correlation is used for fully developed laminar liquid flow. Petukhov-Kirillov (1970) correlation is used for fully developed turbulent liquid flow. Dittus-Boulter (1930) correlation is used for fully developed turbulent gas flow.

Gas/Liquid Two-Phase Heat Transfer Models

For gas/liquid two-phase flow, some previous heat-transfer correlations were developed for different flow patterns. For example, Aggour (1978) correlation is for bubbly flow; Rezkallah-Sims (1987) is for intermittent flow and Ravipudi-Godbold (1987) is for annular flow. The development of a general heat-transfer model which can cover different flow patterns is necessary. In the correlation of general heat-transfer coefficient, Kim *et al.* (2006) introduced a flow pattern factor which is referred as effective wetted-perimeter. Mechanistic models were developed by Manabe *et al.* (2003) and Zhang *et al.* (2006).

Manabe Heat Transfer Model

In Manabe heat transfer model, flow pattern and hydrodynamics are predicted by Ansari *et al.* (1994) model.

Bubbly Flow

Bubbly flow is treated as pseudo single-phase, thus same model for single-phase can be implemented. Liquid properties are used for the pseudo single-phase properties. Velocity used in the model is the mixture velocity.

Annular Flow

For annular flow, the heat transfer between the liquid film and gas core is negligible, thus only heat transfer between the liquid film and surroundings is taken into consideration. Based on this assumption, heat balance equation is developed and flow regime is divided into turbulent and laminar based on the film Reynolds number.

Intermittent Flow

For intermittent flow, heat transfer coefficient is a weighted average between the Taylor bubble region and liquid slug region. This average is based on the ratio of Taylor bubble and the slug unit lengths.

Zhang et al. Unified Heat Transfer Model

Zhang *et al.* (2006) proposed unified model of heat transfer for gas/liquid pipe flows at all inclination angles.

Bubbly Flow and Dispersed Bubble Flow

Bubbly flow is treated as pseudo single-phase. Fluid properties are adjusted with liquid holdup.

Stratified/Annular Flow

For stratified or annular flow, heat exchange between liquid film and the gas core is considered. Thus the heat loss across the liquid film is resulted from the heat exchange with gas core and the surroundings.

Slug Flow

Temperature variation across the slug unit is modeled. The average temperature is used to derive the overall heat transfer coefficient.

Modeling Approaches

After initial review the available heat transfer models for pipe flow, no mechanistic model for gas/oil/water pipe flow has been found. More literature search will be carried on gas/oil/water heat transfer modeling. The following plan for the development of a new gas/oil/water heat transfer model is proposed.

1st Approach

Combine oil and water phases into a pseudo single-phase. Then, convert the three-phase outputs from the hydrodynamic calculation into two-phase parameters to conduct heat transfer calculations by implementing the Zhang *et al.* unified heat transfer model.

TUFFP Excel VBA software package for wellbore and pipeline thermal calculations will be updated with the result of this approach.

2nd Approach

Develop a unified heat transfer model based on specific thermal balance equations for gas/oil/water three-phase flow.

References

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

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Kim, D., Ghajar, A.J., "A General Heat Transfer Correlation for Non-Boiling Gas-Liquid Flow with Different Flow Patterns in Horizontal Pipes," International Journal of Multiphase Flow **32**, 447-465 (2006).

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

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).

Fluid Flow Projects

Questionnaire Results

Eduardo Pereyra

Advisory Board Meeting, May 12, 2011

Questionnaire

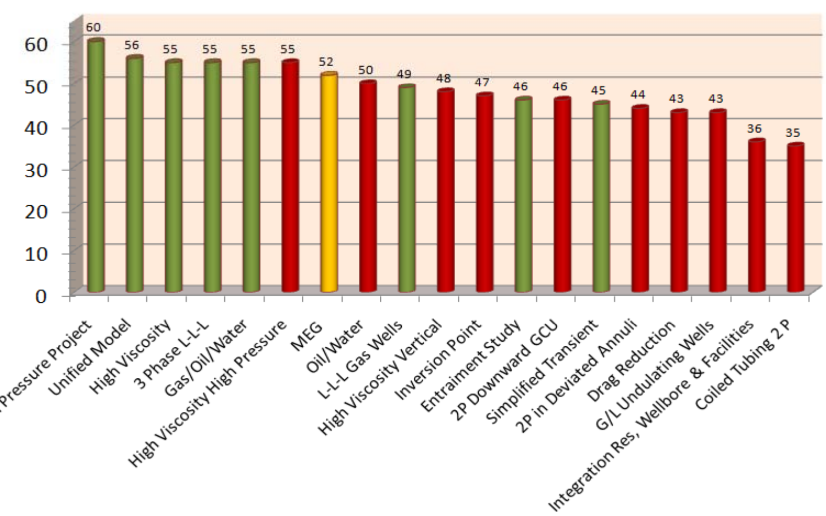
- Total Projects: 19
- Ongoing Projects: 8
- Potential Projects: 11
  - New Potential Projects 4:
    - Two-Phase Flow in Deviated and Horizontal Annuli
    - Two-Phase Flow in Full Scale Coiled Tubing
    - Scale-up of High Oil Viscosity Effects on Multiphase Flow Behavior
    - Effect of MEG (Monoethylene glycol) on multiphase flow behavior

Fluid Flow Projects Advisory Board Meeting, May 12, 2011

Ongoing Projects

Rank	Project
1	Up-scaling Studies in Multiphase Flow
2	Unified Modeling of Multiphase Pipe Flows (Including Gas-Liquid, Oil-Water and Gas-Oil-Water Flows)
3	Effect of High Viscosity on Multiphase Flow Behavior
3	Three-Phase Flow in Near-Horizontal Pipelines with Low Oil-Water Loading
3	Gas-Oil-Water Flow in Pipes
6	Liquid-Loading from Gas Wells
9	Closure Laws for Droplet-Homophase Interaction
10	Simplified Transient Multiphase Flow Model

Results



Questions and Comments

?

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Fluid Flow Projects

Effects of MEG on Multiphase Flow Behavior

Eduardo Pereyra

Advisory Board Meeting, May 12, 2011

Outline

- Objectives
- Literature Review
- Project Proposal
- Future Activities

Objectives

- Collect Flow Pattern, Holdup, Pressure Drop Data on a 6” Pipe With and Without MEG
- Benchmark Steady State Models, Document Discrepancies
- Propose Improvements If Needed

Literature Review

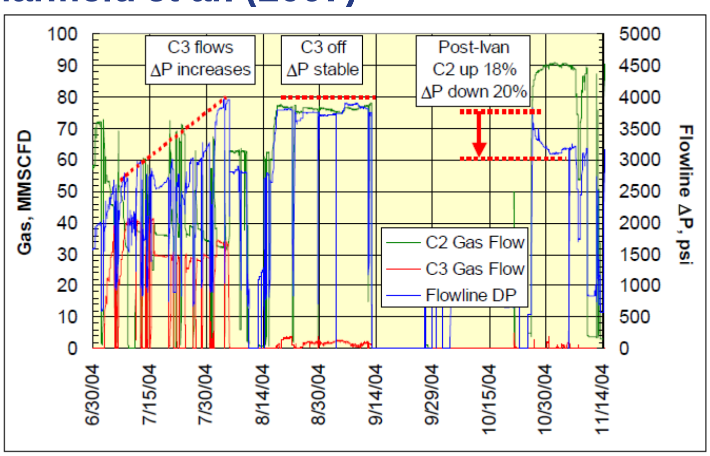
- Wilson *et al*. (2004)
  - Multiphase Flow Modeling Verification for
    - Gas + Condensate + Fresh Water
    - Gas + Condensate + Water (50 wt% MEG)
    - Gas + Condensate + Water (42 wt% MeOH)
  - No Major Differences for Three Different
  - No Data Presented

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 on

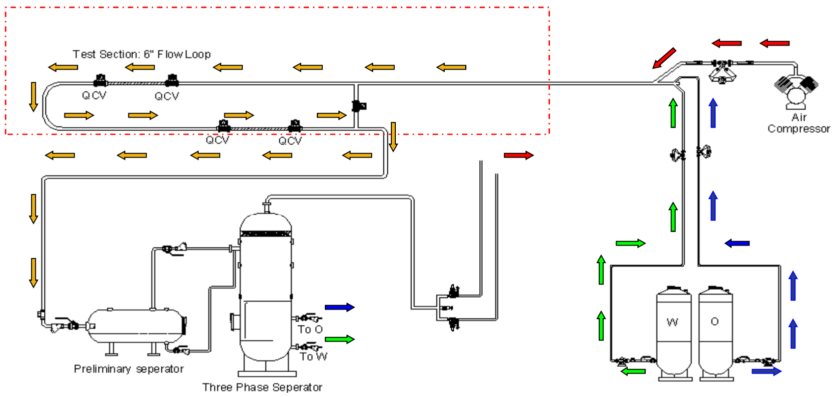
Literature Review

- Manfield *et al*. (2007)



Project Proposal

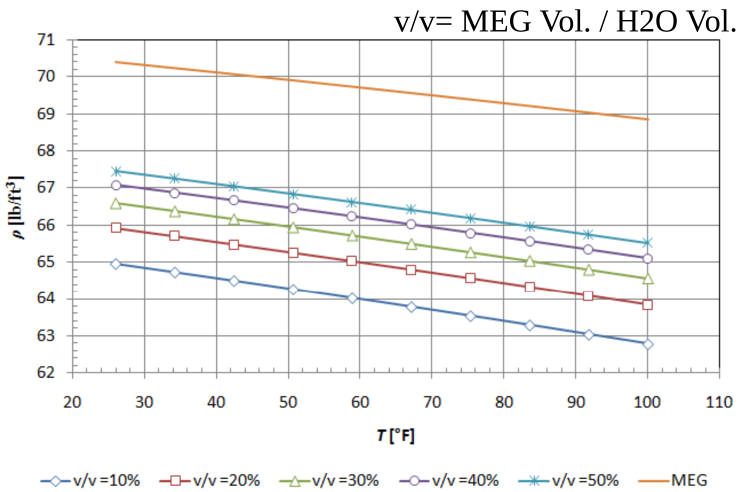
6-in ID Low Liquid Loading Facility



Average Ambient Temperature

- Average High
- Average Low

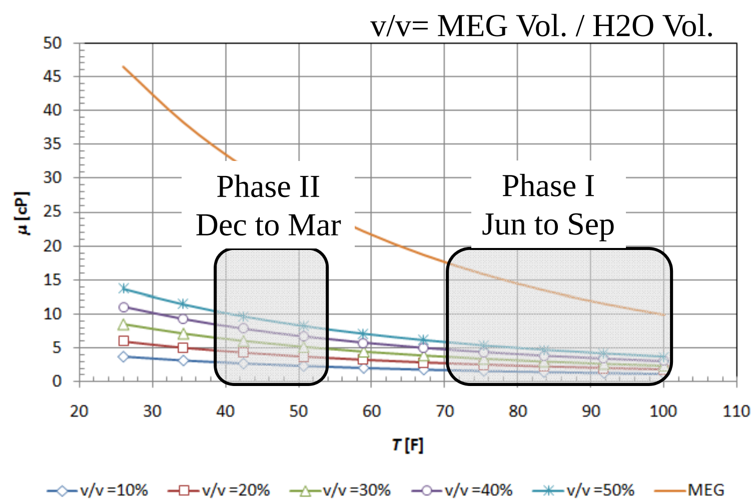
Water+MEG Densities



Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Testing Range



Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Project Proposal

- Phase I : High Temperature Test
- Phase II: Low Temperature Test
- Phase III: Stable Emulsion Effects (?)

Future Activities

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

Questions and Comments

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Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Fluid Flow Projects

Business Report

Cem Sarica

Advisory Board Meeting, May 12, 2011

Membership and Collaboration Status

- Current Membership Status
  - Membership Increased to 16
  - 15 Industrial and MMS
- Efforts Continue to Increase TUFFP Membership
  - PEMEX's Membership in Progress
  - Saudi Aramco is Expected to Rejoin for 2012
- Collaboration with Seoul National University Continues
  - Visiting Research Scholars and Financial Contribution

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Personnel Changes

- Dr. Eduardo Pereyra Joins TUFFP/TUHOP Team
- Norman Stegall Replaces Brandon Kelsey

Publications and Papers

- Alsarkhi, A. and Sarica, C. "New Dimensionless Parameters and a Power Law Correlation for Pressure Drop of Gas-Liquid Flows in Horizontal Pipelines," SPE Journal Project Facilities & Construction December 2010
- Alsarkhi, A., Sharma, A., Sarica, C., and Zhang, H. Q.: "Modeling of Oil-Water Flow Using Energy Minimization Concept," *International Journal of Multiphase Flow,* pp. 326-335, 37/4*.* May 2011
- 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)" Accepted for publication in *International Journal of Multiphase Flow*

Publications and Papers …

- Alsarkhi, A., Sarica, C., and Magrini, K.: "Inclination Effects on Wave Characteristics in Annular Gas-Liquid Flows," Accepted for Publication in *AIChE* 2011
- Zhang, H. Q., and Sarica, C.: "Low Liquid Loading Gas/Liquid Pipe Flow," JNGSE-D-10-00101R1, Accepted for Publication in *Journal of Natural Gas Science & Engineering*
- Zhang, H. Q., and Sarica, C.: "A Model for Wetted Wall Fraction and Gravity Center of Liquid Film in Gas-Liquid Pipe Flow," Accepted for Publication in *Society of Petroleum Engineers Journal*

Next Advisory Board Meetings

- Tentative Schedule
  - October 25, 2011
    - TUHOP Meeting
    - TUFFP Workshop
    - Facility Tour
    - TUHOP/TUHFP/TUFFP Reception
  - October 26, 2011
    - TUFFP Meeting
    - TUFFP/TUPDP Dinner
  - October 27, 2011
    - TUPDP Meeting
- Venue is The University of Tulsa

Financial Report

- Year 2010 Closing
  - TUFFP Industrial Account
  - TUFFP BOEMRE Account
- Year 2011 Update
  - TUFFP Industrial Account
  - TUFFP BOEMRE Account

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

2010 Industrial Account Summary

(Prepared April 22, 2011)

Anticipated Reserve Fund Balance on January 1, 2010					**($9,195)**
Income for 2010					
	2010 Membership Fees (13 @ $48,000 - exludes MMS)				**624,000**
	Facility Utilization Fee (SNU)				**55,000**
Total Budget					**$ 669,805**
Projected Budget/Expenditures for 2010					
		Projected Budget (Fall 2009)	**Revised Budget (April 2010)**	**2010 Expenditures (April 2011)**	
90101 - 90103	Faculty Salaries	29,074.14	918.10	981.10	
90600 - 90609	Professional Salaries	47,628.54	53,310.06	52,114.93	
90700 - 90703	Staff Salaries	35,262.50	35,291.52	35,984.07	
91000	Student Salaries - Monthly	41,550.00	43,725.00	49,700.00	
91100	Student Salaries - Hourly	15,000.00	10,000.00	8,389.07	
91800	Fringe Benefits	38,068.16	30,986.49	30,528.57	
81801	Tuition & Student Fees	17,898.00	26,637.00	27,296.00	
92102	Student Fringe		1,762.00	2,488.00	
93100	General Supplies	3,000.00	3,000.00	2,279.37	
93101	Research Supplies	50,000.00	60,000.00	135,761.76	
93102	Copier/Printer Supplies	500.00	500.00	54.65	
93104	Computer Software	4,000.00	3,000.00	2,992.06	
93106	Office Supplies	2,000.00	2,000.00	1,036.27	
93200	Postage and Shipping	500.00	500.00	1,792.40	
93300	Printing and Duplicating	2,000.00	2,000.00	2,339.67	
93400	Telecommunications	3,000.00	1,700.00	2,072.51	
93500	Membership	1,000.00	1,000.00	204.00	
93601	Travel - Domestic	10,000.00	10,000.00	5,253.21	
93602	Travel - Foreign	10,000.00	10,000.00	7,225.96	
93700	Entertainment	10,000.00	10,000.00	15,707.67	
94813	Outside Services	20,000.00	20,000.00	100,748.00	
95103	Equipment Rental			20,940.00	
95200	F&A (55.6%)	93,694.44	79,679.07	76,895.35	
98901	Employee Recruiting	3,000.00		435.09	
99001	Equipment	200,000.00	257,868.00	99,671.41	
99002	Computers	8,000.00	-	16,613.80	
99300	Bank Charges	40.00	40.00	60.00	
Total Anticipated Expenditures		**645,215.78**	**663,917.24**	**699,564.92**	
Anticipated Reserve as of 12/31/10					**(29,760.26)**

2010 BOEMRE (Formerly MMS) Account Summary

(Prepared April 25, 2011)

Reserve Balance as of 12/31/09			**16,805.82**
2010 Budget			**48,000.00**
Total Budget			**64,805.82**

Projected Budget/Expenditures for 2010

	Budget	**2010 Expenditures**	
91000 Students - Monthly	27,900.00	31,900.00	
91202 Student Fringe Benefits		1,160.00	
95200 F&A	15,512.40	18,964.27	
Total Anticipated Expenditures as of 12/31/10	**43,412.40**	**52,024.27**	
Total Anticipated Reserve Fund Balance as of 12/31/10			**12,781.55**

2011 Industrial Account

(Prepared April 26, 2011)

Anticipated Reserve Fund Balance on January 1, 2011					**($29,760)**
Income for 2011					
	2011 Anticipated Membership Fees (15 @ $55,000 - exludes MMS)				**825,000**
	Facility Utilization Fee (SNU)				**55,000**
	Facility Utilization Fee (Foam Project)				**60,000**
Total Budget					**$ 910,240**
Projected Budget/Expenditures for 2010					
		Projected Budget 11/3/10	**Revised Budget April 2011**	**Expenditures 4/26/11**	
90101 - 90103	Faculty Salaries	38,481.88	38,481.88	3,772.74	
90600 - 90609	Professional Salaries	71,906.23	51,656.23	17,217.57	
90700 - 90703	Staff Salaries	28,306.09	31,289.67	7,349.90	
90800	Part-time/Temporary		24,000.00		
91000	Student Salaries - Monthly	43,950.00	43,950.00	13,200.00	
91100	Student Salaries - Hourly	15,000.00	15,000.00	1,235.36	
91800	Fringe Benefits	48,542.97	42,500.00	9,919.06	
92102	Fringe Benefits (Students)		3,516.00	792.00	
81801	Tuition & Student Fees		-	526.00	
81806	Fellowship			750.00	
93100	General Supplies	3,000.00	3,000.00	2,004.31	
93101	Research Supplies	100,000.00	100,000.00	4,212.97	
93102	Copier/Printer Supplies	500.00	500.00	75.08	
93104	Computer Software	4,000.00	4,000.00	-	
93106	Office Supplies	2,000.00	2,000.00	474.32	
93200	Postage and Shipping	500.00	500.00	293.85	
93300	Printing and Duplicating	2,000.00	2,000.00	108.76	
93400	Telecommunications	3,000.00	3,000.00	-	
93500	Membership	1,000.00	1,000.00	-	
93601	Travel - Domestic	10,000.00	10,000.00	601.90	
93602	Travel - Foreign	10,000.00	10,000.00	-	
93700	Entertainment	10,000.00	16,000.00	510.90	
94813	Outside Services	20,000.00	40,000.00	2,488.64	
95103	Equipment Rental			8,605.80	
95200	F&A (55.6%)	103,565.56	107,094.00	20,093.05	
98901	Employee Recruiting	3,000.00	3,000.00		
99001	Equipment	250,000.00	250,000.00	68,430.00	
99002	Computers	8,000.00	8,000.00	2,990.06	
99300	Bank Charges	40.00	40.00	32.00	
Total Anticipated Expenditures		**776,792.73**	**810,527.78**	**165,684.27**	
Anticipated Reserve as of 12/31/11					**99,711.96**

2011 BOEMRE Account

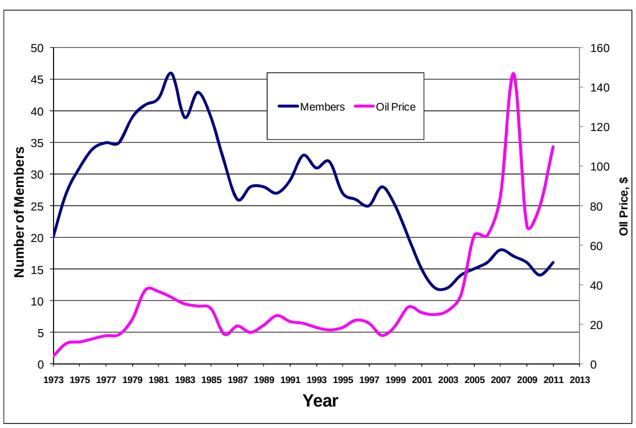
(Prepared April 25, 2011)

Reserve Balance as of 12/31/10				**12,781.55**
2011 Budget				**48,000.00**
Total Budget				**60,781.55**

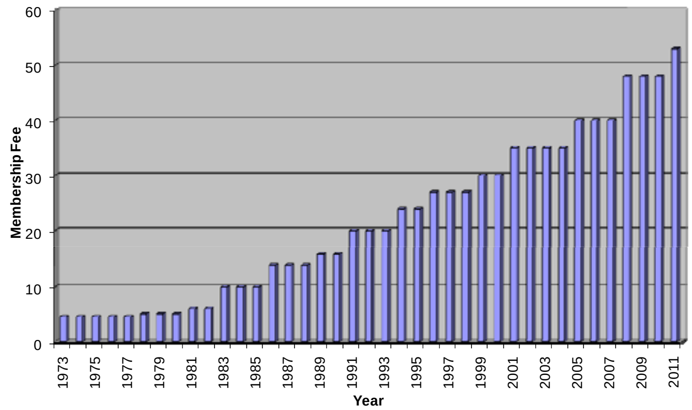
Projected Budget/Expenditures for 2011

	Budget	**Revised Budget April 2011**	**2011 Expenditures**	
91000 Students - Monthly	29,000.00	36,425.00	36,425.00	
91202 Student Fringe Benefits	2,320.00	2,914.00	2,914.00	
95200 F&A	15,196.00	20,252.00	20,252.30	
Total Anticipated Expenditures as of 12/31/11	**46,516.00**	**59,591.00**	**59,591.30**	
Total Anticipated Reserve Fund Balance as of 12/31/11				**1,190.25**

History – Membership



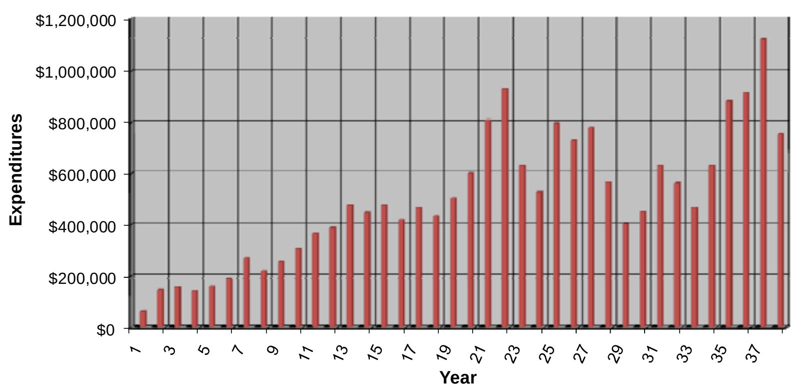
History – Membership Fees



Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

History - Expenditures



Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Membership Fees

- 2011 Membership Dues
  - 3 Unpaid Memberships

Fluid Flow Projects

Advisory Board Meeting, May 12, 2011

Introduction

This semi-annual report is submitted to Tulsa University Fluid Flow Projects (TUFFP) members to summarize activities since the November 3, 2010 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 76th semi-annual Advisory Board meeting to be held in OneOK Club of H. A. Chapman Stadium of the University of Tulsa Main Campus, 3112 East 8th Street, Tulsa, Oklahoma on Thursday, May 12, 2011.

The activities will start with Tulsa University High Viscosity Projects (TUHOP) Advisory Board meeting on May 11, 2011 between 8:15 a.m. and noon in OneOK Club. Between 1:00 and 3:30 p.m. on May 11, 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 May 11, 2011 between 4:00 and 5:30 p.m. Following the tour, there will be a TUHOP/TUFFP reception between 6:00 p.m. and 9:30 p.m. in OneOK Club.

TUFFP Advisory Board meeting will convene at 8:00 a.m. on May 12 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 OneOK Club.

The Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board meeting will be held on May 13 in OneOK Club, between 8:00 a.m. and 1:15 p.m.

The reception and the dinner will provide an opportunity for informal discussions among members, guests, and TU staff and students.

Several TUFFP/TUPDP/TUHOP facilities will be operating during the tour. An opportunity will also be available to view the hydrate flow loop.

The following dates have tentatively been established for Fall 2011 Advisory Board meetings. The venue for Fall 2011 Advisory Board meetings is tentatively set to be the University of Tulsa Main Campus.

2011 Fall Meetings

October 25, 2011	Tulsa University High Viscosity Oil Projects (TUHOP) JIP Meeting
	Tulsa University Fluid Flow Projects (TUFFP) Workshop
	Facility Tour
	TUHOP/TUFFP Reception
October 26, 2011	Tulsa University Fluid Flow Projects (TUFFP) Advisory Board Meeting
	TUFFP/TUPDP Reception
October 27, 2011	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 has joined TUFFP/TUHOP team as a Research Associate effective January 2011. 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. Brandon Kelsey, the electro-mechanical technician, resigned to take a position with Zeeco, a process design and construction company serving downstream oil and gas business after four years of service to our projects. Mr. Norman Stegall has recently been hired as the replacement of Brandon Kelsey's replacement. Mr. Stegall comes to us from Tulsa Public School (TPS) System. He spent over 25 years with TPS working for their facilities support department.

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, is pursuing his MS degree in Petroleum Engineering. Ben has received a BS degree in Chemical Engineering from Birla Institute of Technology and Science University in 2008. Ben is studying the high oil viscosity multiphase flow.

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. She is pursuing Ph.D. in Petroleum Engineering. Mujgan is assigned to high pressure effects on multiphase flow project.

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 received prestigious Fulbright Scholarship to study abroad. Rosmer is pursuing and MS degree in petroleum engineering. She is assigned to high viscosity two-phase flow project.

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.

One new graduate student, Mr. Feras Al-Ruhaimani, from Kuwait has recently joined TUFFP team as a Research Assistants to pursue 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 will be assigned a project in High Viscosity Oil Multiphase Flow.

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 Spring Research Assistant Status

Name	*Origin*	*Stipend*	*Tuition*	*Degree Pursued*	*TUFFP Project*	*Completion Date*
Kiran Gawas	India	Yes – TUFFP	Waived (TU)	Ph.D. – PE	Three-phase Gas-Oil-Water Low Liquid Loading	Spring 2012
Benin (Ben) Chelinsky Jeyachandra	India	Yes – TUFFP	Waived (BOEMRE)	MS – PE	High Viscosity Oil and Gas Flow in Inclined Pipes	Fall 2011
Ge (Max) Yuan	PRC	Yes – TUFFP	Waived – (BOEMRE)	MS – PE	Liquid Unloading from Gas Wells	Fall 2011
Mujgan Guner	Turkey	Yes – TUFFP	Waived – (TU)	Ph.D. – PE	Up-scaling Studies in Two-phase Flow	Spring 2014
Rosmer Brito	Venezuela	No – Fulbright	No – Fulbright	MS – PE	High Viscosity Oil Two-phase Flow	Spring 2012
Wei Zheng	PRC	Partial – TU	Waived – (TU)	MS – PE	Unified Heat Transfer Modeling of Gas/Oil/Water Pipe Flow	Spring 2012
Jinho Choi	South Korea	SNU	N/A	Ph.D. (SNU)	Simplified Transient Gas-Liquid Two-Phase Flow Modeling	Spring 2013
Hoyoung Lee	South Korea	SNU	N/A	Ph.D. (SNU)	Two-phase Gas-Liquid Flow Modeling Using Energy Minimization Concept	Spring 2013
Feras Al-Ruhaimani	Kuwait	KU	KU	Ph.D. PE	High Viscosity Oil Multiphase Flow	Spring 2014

Membership

The current membership of TUFFP increases to 16: 15 industrial members and Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE) formerly, MMS of Department of Interior (MMS). The new members are Vetco Gray (GE) and Aspen Tech.

Our efforts to increase the TUFFP membership level continues. PEMEX has indicated that they would like to rejoin TUFFP in 2011. Saudi Aramco will consider rejoining in 2012.

Table 2 lists all the current 2010 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 one 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	Marathon Oil Company
Baker Atlas	BOEMRE
BP Exploration	Petrobras
Chevron	Schlumberger
ConocoPhillips	Shell Global Solutions
Exxon Mobil	SPT
JOGMEG	Total
KOC	Vetco Gray (GE)

Equipment and Facilities Status

Test Facilities

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

A new diesel powered portable air compressor is purchased to serve multiple TUFFP projects. Currently, the compressor is being used for low liquid loading project utilizing 6 in. ID Low pressure flow loop.

Three-phase 3 in. ID facility is being 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.

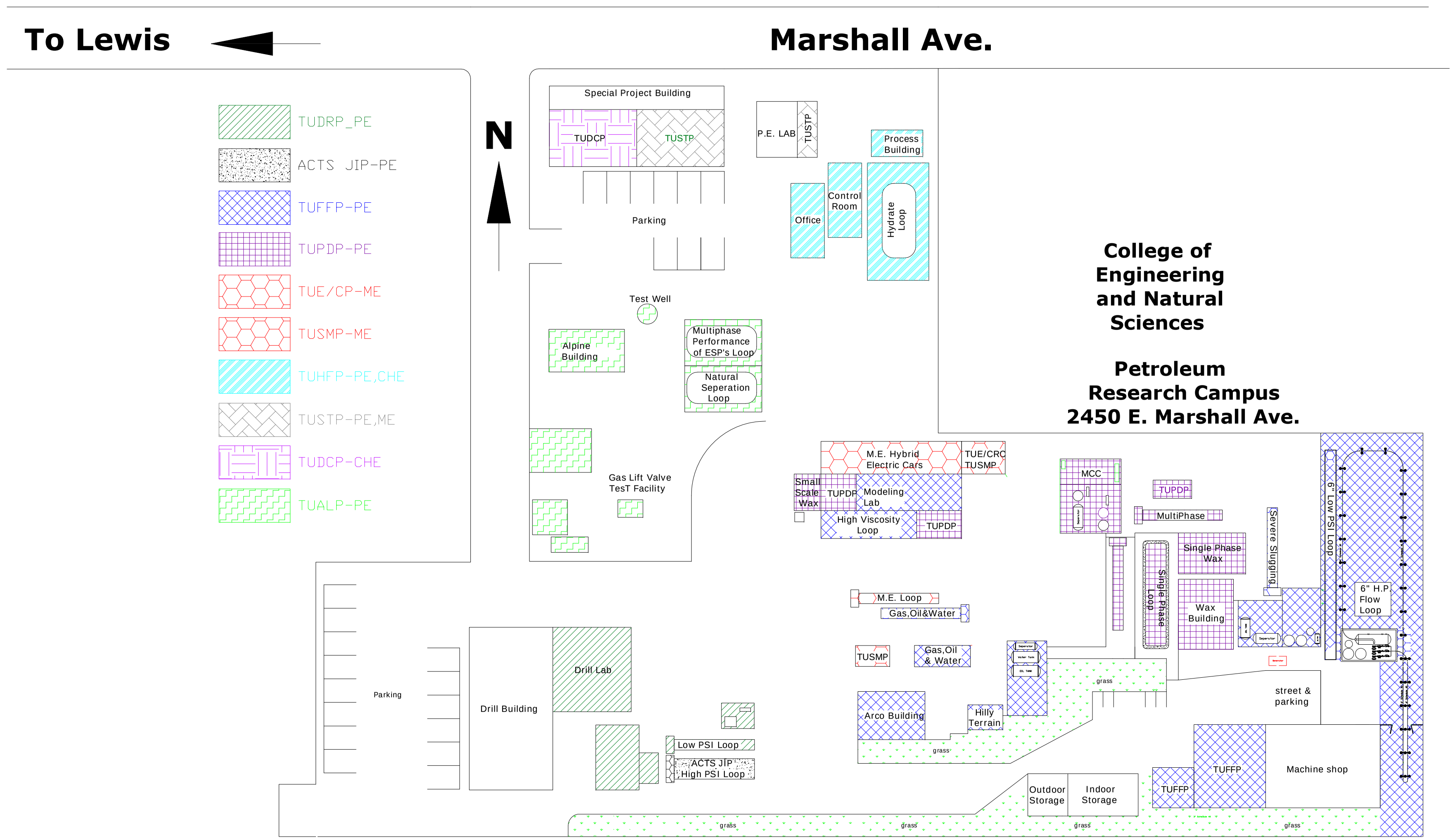


Figure 1 – Site Plan for the North Campus Research Facilities

Financial Status

TUFFP maintains separate accounts for industrial and U.S. government members. Thus, separate accounts are maintained for the Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE) formerly, MMS funds.

Table 3 presents a financial analysis of income and expenditures for the 2010 Industrial member account as of April 26, 2011. Also shown are previous 2010 budgets that have been reported to the members. The total industry expenditures for 2010 are estimated to be $699,564.92. This results in a deficit of $29,760.26 to be carried to 2011 fiscal year.

Table 4 presents a financial analysis of expenditures and income for the BOEMRE account for 2010. This account is used primarily for graduate student stipends. A balance of $12,781.55 is anticipated to carry over to 2011.

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, BOEMRE 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 2010.

Tables 5-6 present the proposed budgets and income for the Industrial, and BOEMRE accounts for 2011. The 2011 TUFFP industrial budged is based on 15 members. This provides $855,000.00 of industrial membership income for 2011. In addition TUFFP receives facility utilization fee from SNU and TUFPPC JIP totaling $115,000.00. The total of the 2011 income and the reserve account is projected to be $910,240.00. The expenses for the industrial member account are revised to be $810,527.78 leaving a carryover balance of $99,711.96. The BOEMRE account is expected to have a carryover of $1,190.25 to 2012.

Table 3: 2010 Industrial Budget Summary

(Prepared April 22, 2011)

Anticipated Reserve Fund Balance on January 1, 2010			**($9,195)**
Income for 2010			
	2010 Membership Fees (13 @ $48,000 - exludes MMS)		**624,000**
	Facility Utilization Fee (SNU)		**55,000**
Total Budget		**$**	**669,805**

Projected Budget/Expenditures for 2010

		Projected Budget (Fall 2009)	Revised Budget (April 2010)	2010 Expenditures (April 2011)
90101 - 90103	Faculty Salaries	29,074.14	918.10	981.10
90600 - 90609	Professional Salaries	47,628.54	53,310.06	52,114.93
90700 - 90703	Staff Salaries	35,262.50	35,291.52	35,984.07
91000	Student Salaries - Monthly	41,550.00	43,725.00	49,700.00
91100	Student Salaries - Hourly	15,000.00	10,000.00	8,389.07
91800	Fringe Benefits	38,068.16	30,986.49	30,528.57
81801	Tuition & Student Fees	17,898.00	26,637.00	27,296.00
92102	Student Fringe		1,762.00	2,488.00
93100	General Supplies	3,000.00	3,000.00	2,279.37
93101	Research Supplies	50,000.00	60,000.00	135,761.76
93102	Copier/Printer Supplies	500.00	500.00	54.65
93104	Computer Software	4,000.00	3,000.00	2,992.06
93106	Office Supplies	2,000.00	2,000.00	1,036.27
93200	Postage and Shipping	500.00	500.00	1,792.40
93300	Printing and Duplicating	2,000.00	2,000.00	2,339.67
93400	Telecommunications	3,000.00	1,700.00	2,072.51
93500	Membership	1,000.00	1,000.00	204.00
93601	Travel - Domestic	10,000.00	10,000.00	5,253.21
93602	Travel - Foreign	10,000.00	10,000.00	7,225.96
93700	Entertainment	10,000.00	10,000.00	15,707.67
94813	Outside Services	20,000.00	20,000.00	100,748.00
95103	Equipment Rental			20,940.00
95200	F&A (55.6%)	93,694.44	79,679.07	76,895.35
98901	Employee Recruiting	3,000.00		435.09
99001	Equipment	200,000.00	257,868.00	99,671.41
99002	Computers	8,000.00	-	16,613.80
99300	Bank Charges	40.00	40.00	60.00
Total Anticipated Expenditures		**645,215.78**	**663,917.24**	**699,564.92**

Anticipated Reserve as of 12/31/10 **(29,760.26)**

Table 4: 2010 BOEMRE Budget Summary

(Prepared April 25, 2011)

Reserve Balance as of 12/31/09			**16,805.82**
2010 Budget			**48,000.00**
Total Budget			**64,805.82**

Projected Budget/Expenditures for 2010

	Budget	**2010 Expenditures**	
91000 Students - Monthly	27,900.00	31,900.00	
91202 Student Fringe Benefits		1,160.00	
95200 F&A	15,512.40	18,964.27	
Total Anticipated Expenditures as of 12/31/10	**43,412.40**	**52,024.27**	
Total Anticipated Reserve Fund Balance as of 12/31/10			**12,781.55**

Table 5: 2011 Industrial Budget

(Prepared April 26, 2011)

Anticipated Reserve Fund Balance on January 1, 2011					**($29,760)**
Income for 2011					
	2011 Anticipated Membership Fees (15 @ $55,000 - exludes MMS)				**825,000**
	Facility Utilization Fee (SNU)				**55,000**
	Facility Utilization Fee (Foam Project)				**60,000**
Total Budget					**$ 910,240**
Projected Budget/Expenditures for 2010					
		Projected Budget 11/3/10	**Revised Budget April 2011**	**Expenditures 4/26/11**	
90101 - 90103	Faculty Salaries	38,481.88	38,481.88	3,772.74	
90600 - 90609	Professional Salaries	71,906.23	51,656.23	17,217.57	
90700 - 90703	Staff Salaries	28,306.09	31,289.67	7,349.90	
90800	Part-time/Temporary		24,000.00		
91000	Student Salaries - Monthly	43,950.00	43,950.00	13,200.00	
91100	Student Salaries - Hourly	15,000.00	15,000.00	1,235.36	
91800	Fringe Benefits	48,542.97	42,500.00	9,919.06	
92102	Fringe Benefits (Students)		3,516.00	792.00	
81801	Tuition & Student Fees		-	526.00	
81806	Fellowship			750.00	
93100	General Supplies	3,000.00	3,000.00	2,004.31	
93101	Research Supplies	100,000.00	100,000.00	4,212.97	
93102	Copier/Printer Supplies	500.00	500.00	75.08	
93104	Computer Software	4,000.00	4,000.00	-	
93106	Office Supplies	2,000.00	2,000.00	474.32	
93200	Postage and Shipping	500.00	500.00	293.85	
93300	Printing and Duplicating	2,000.00	2,000.00	108.76	
93400	Telecommunications	3,000.00	3,000.00	-	
93500	Membership	1,000.00	1,000.00	-	
93601	Travel - Domestic	10,000.00	10,000.00	601.90	
93602	Travel - Foreign	10,000.00	10,000.00	-	
93700	Entertainment	10,000.00	16,000.00	510.90	
94813	Outside Services	20,000.00	40,000.00	2,488.64	
95103	Equipment Rental			8,605.80	
95200	F&A (55.6%)	103,565.56	107,094.00	20,093.05	
98901	Employee Recruiting	3,000.00	3,000.00		
99001	Equipment	250,000.00	250,000.00	68,430.00	
99002	Computers	8,000.00	8,000.00	2,990.06	
99300	Bank Charges	40.00	40.00	32.00	
Total Anticipated Expenditures		**776,792.73**	**810,527.78**	**165,684.27**	
Anticipated Reserve as of 12/31/11					**99,711.96**

Table 6: 2011 BOEMRE Budget

(Prepared April 25, 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	36,425.00	
91202	Student Fringe Benefits	2,320.00	2,914.00	2,914.00	
95200	F&A	15,196.00	20,252.00	20,252.30	
Total Anticipated Expenditures as of 12/31/11		**46,516.00**	**59,591.00**	**59,591.30**	
Total Anticipated Reserve Fund Balance as of 12/31/11					**1,190.25**

Miscellaneous Information

Fluid Flow Projects Short Course

The 34th TUFFP "Two-Phase Flow in Pipes" short course was taught May 17-21, 2010 for 10 people from 6 different companies.

The 35th TUFFP "Two-Phase Flow in Pipes" short course offering is scheduled for May 16-20, 2011. 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 spend very productive 2 ½ months with TUFFP last summer. During his stay he has helped TUFFP graduate students and worked on the droplet homo-phase project concentrating on the analysis of the film and entrainment fraction data acquired by Kyle Magrini.

Once more, Dr. Al-Sarkhi has accepted our offer to spend his 2011 summer in TUFFP. He will be working with TUFFP Research Assistants and Associates on their research projects.

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, will be held 15-17 of June 2011 in Cannes, France. 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. The detailed information about the conference can be found in BHRg's (www.brhgroup.com). There are two papers with TUFFP contributions to be presented

Publications & Presentations

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

1) Alsarkhi, A. and Sarica, C. "New Dimensionless Parameters and a Power Law Correlation for Pressure Drop of Gas-Liquid Flows in Horizontal Pipelines," SPE Journal Project Facilities & Construction December 2010.
2) Alsarkhi, A., Sharma, A., Sarica, C., and Zhang, H. Q.: "Modeling of Oil-Water Flow Using Energy Minimization Concept," *International Journal of Multiphase Flow*, pp. 326-335, 37/4. May 2011.
3) 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)" Accepted for publication in *International Journal of Multiphase Flow*.
4) Alsarkhi, A., Sarica, C., and Magrini, K.: "Inclination Effects on Wave Characteristics in Annular Gas-Liquid Flows," Accepted for Publication in *AIChE* 2011.
5) Zhang, H. Q., and Sarica, C.: "Low Liquid Loading Gas/Liquid Pipe Flow," JNGSE-D-10-00101R1, Accepted for Publication in *Journal of Natural Gas Science & Engineering*.
6) Zhang, H. Q., and Sarica, C.: "A Model for Wetted Wall Fraction and Gravity Center of Liquid Film in Gas-Liquid Pipe Flow," Accepted for Publication in *Society of Petroleum Engineers Journal*.

Tulsa University Paraffin Deposition Projects (TUPDP) Activities

The forth three year phase of TUPDP has recently started. The studies concentrate on the paraffin deposition characterization of single-phase turbulent flow with new oils, gas-oil-water paraffin deposition, restart of gelled flow lines 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 equivalent of one year TUFFP membership fee will be paid to TUFFP. Current industrial members of the JIP are Chevron, ConocoPhillips, Marathon, Shell, Nalco and Multichem. Nalco and Multichem will each pay $30,000 facility utilization fee.

Two-Phase Flow Calendar

Several technical meetings, seminars, and short courses involving two-phase flow in pipes are scheduled for 2011. Table 9 lists meetings that would be of interest to TUFFP members.

Table 9

Meeting and Conference Calendar

2011

May 11	TUHOP Spring Advisory Board Meeting, Tulsa, Oklahoma
	TUFFP Spring Workshop, Tulsa, Oklahoma
May 12	TUFFP Spring Advisory Board Meeting, Tulsa, Oklahoma
May 13	TUPDP Spring Advisory Board Meeting, Tulsa, Oklahoma
June 14 – 17	Brasil Offshore Exhibition and Conference, Macae, Brasil
June 15 - 17	BHRg's 15th International Conference on Multiphase Technology, Cannes, France
Sept. 6 – 8	Offshore Europe, Aberdeen UK
Oct. 4 – 6	OTC Brasil, Rio de Janeiro, RJ, Brazil
Oct. 25	TUHOP Fall Advisory Board Meeting, Tulsa, Oklahoma
	TUFFP Fall Workshop, Tulsa, Oklahoma
Oct. 26	TUFFP Fall Advisory Board Meeting, Tulsa, Oklahoma
Oct. 27	TUPDP Fall Advisory Board Meeting, Tulsa, Oklahoma
Oct. 30 – Nov. 2	SPE Annual Technical Conference and Exhibition, Denver, CO, USA

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).

Appendix B

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Appendix C

History of Fluid Flow Projects Membership

		1973	
1.	TRW Reda Pump	12 Jun. '72	T: 21 Oct. '77
2.	Pemex	15 Jun. '72	T: 30 Sept. '96 R: Dec '97 T: 2010
3.	Getty Oil Co.	19 Jun. '72	T: 11 Oct. '84 with sale to Texaco
4.	Union Oil Co. of California	7 Jul. '72	T: for 2001
5.	Intevep	3 Aug. '72	TR: from CVP in '77; T: 21 Jan '05 for 2006
6.	Marathon Oil Co.	3 Aug. '72	T: 17 May '85 R: 25 June '90 T: 14 Sept. '94 R: 3 June '97 **Current**
7.	Arco Oil and Gas Co.	7 Aug. '72	T: 08 Dec. '97
8.	AGIP	6 Sep. '72	T: 18 Dec. '74
9.	Otis Engineering Corp.	4 Oct. '72	T: 15 Oct. '82
10.	ConocoPhillips, Inc.	5 Oct. '72	T: Aug. '85 R: 5 Dec. '86 **Current**
11.	Mobil Research and Development Corp.	13 Oct. '72	T: 27 Sep. 2000
12.	Camco, Inc.	23 Oct. '72	T: 15 Jan. '76 R: 14 Mar. '79 T: 5 Jan. '84
13.	Crest Engineering, Inc.	27 Oct. '72	T: 14 Nov. '78 R: 19 Nov. '79 T: 1 Jun. '84
14.	Chevron	3 Nov. '72	**Current**
15.	Aminoil	9 Nov. '72	T: 1 Feb. '77

16.	Compagnie Francaise des Petroles (TOTAL)	6 Dec. '72	T: 22 Mar. '85 R: 23 Oct. '90 T: 18 Sep. '01 for 2002 R: 18 Nov. '02 **Current**
17.	Oil Service Co. of Iran	19 Dec. '72	T: 20 Dec. '79
18.	Sun Exploration and Production Co.	4 Jan. '73	T: 25 Oct. '79 R: 13 Apr. '82 T: 6 Sep. '85
19.	Amoco Production Co. (now as BP Amoco)	18 May '73	
20.	Williams Brothers Engrg. Co.	25 May '73	T: 24 Jan. '83
	1974		
21.	Gulf Research and Development Co.	20 Nov. '73	T: Nov. '84 with sale to Chevron
22.	El Paso Natural Gas Co.	17 Dec. '73	T: 28 Oct. '77
23.	Arabian Gulf Exploration Co.	27 Mar. '74	T: 24 Oct. '82
24.	ExxonMobil Upstream Research	27 Mar. '74	T: 16 Sep. '86 R: 1 Jan. '88 T: 27 Sep. 2000 R: 2007 **Current**
25.	Bechtel, Inc.	29 May '74	T: 14 Dec. '76 R: 7 Dec. '78 T: 17 Dec. '84
26.	Saudi Arabian Oil Co.	11 Jun. '74	T: for 1999
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.	Vetco Gray (GE)		**Current**
83.	Aspen Technology, Inc.		**Current**

Note: T = Terminated; R = Rejoined; and TR = Transferred

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