THE UNIVERSITY of TULSA

McDougall School of Petroleum Engineering

Fluid Flow Projects

Eighty First Semi-Annual Advisory Board Meeting Brochure and Presentation Slide Copy

September 25, 2013

Tulsa University Fluid Flow Projects
Eighty-First Semi-Annual Advisory Board Meeting
September 24 - 25, 2013

Agenda

Tuesday, September 24, 2013

11:30 a.m.	TUFFP Workshop Luncheon Renaissance Tulsa Hotel & Convention Center 6808 S 107th E Ave Tulsa, Oklahoma 74133	
12:30 p.m.	TUFFP Workshop Renaissance Tulsa Hotel & Convention Center 6808 S 107th E Ave Tulsa, Oklahoma 74133	
2:00	TUFFP 6” High Pressure Facility Utilization Discussion	
4:00	TUFFP Facility Tour University of Tulsa North Campus 2450 East Marshall Tulsa, Oklahoma 74110	
6:00	TUFFP Reception Renaissance Tulsa Hotel & Convention Center 6808 S 107th E Ave Tulsa, Oklahoma 74133	

Wednesday, September 25, 2013

TUFFP Advisory Board Meeting
Renaissance Tulsa Hotel & Convention Center
6808 S 107th E Ave
Tulsa, Oklahoma 74133

8:00 a.m.	Breakfast	
8:30	Introduction	Cem Sarica
8:45	Progress Report	
	Effects of MEG on Multiphase Flow Behavior	Hamid Karami
	6” High Pressure Facility Single-Phase Tests	Jon Conner
	High Pressure Effects on Two-Phase Oil-Gas Low Liquid Loading Flow	Duc Vuong
10:00	Coffee Break	
10:15	Progress Reports	
	Liquid Loading of Gas Wells with Deviations from 45 to 90°	Yasser Alsaadi

	Onset of Liquid Accumulation in Oil and Gas Pipelines	Yilin Fan
	TUFFP Unified Model Improvement & Update	Carlos Torres
	Database Development	Jinho Choi
12:00 p.m.	Lunch	
1:00	Progress Report	
	Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Pipes	Feras Alruhamani
	Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Downward Flow	Sunghoon Chung
	Revisit of Pipe Inclination on Flow Characteristics of High Viscosity Oil-Gas Two-Phase Flow	Samet Ekinci
	Pipe Diameter Effect on High Viscosity Oil-Gas Two-Phase Horizontal Flow	Taewoo Kim
2:15	Coffee Break	
2:30	Progress Reports	
	Use of Energy and Minimum Energy Dissipated Concept in Multiphase Flow	Abdel Al-Sarkhi
	Unified Wallis's Type Interfacial Friction Factor For Predicting the Pressure Drops In Annular- Churn-Slug Flows	Abdel Al-Sarkhi
	TUHOP Facility Incorporation	Cem Sarica
3:45	Business Report	Cem Sarica
4:00	General Discussion	
4:15	Adjourn	
6:00	TUFFP/TUPDP Reception Renaissance Tulsa Hotel & Convention Center 6808 S 107th E Ave Tulsa, Oklahoma 74133	

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Executive Summary

Progress updates on each research project are provided in this Advisory Board meeting 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. One of the objectives of TUFFP for gas-oil-water research is to improve the closure relationships required for multiphase flow models such as the TUFFP unified model. This objective is addressed in various projects.

- *"Oil Viscosity Effects on 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.

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

  1. *Inclination Angle Effects:* The objective is to conduct a study for inclination angles of -2° and +2°. A complete study was conducted by Jeyachandra (2011). Further performance analysis of the used capacitance sensors indicated that some of the holdup data of Jeyachandra needs to be retaken. In addition to inclined flow data, 3-in. horizontal flow data will be acquired through the return line of the facility to investigate pipe diameter effects. One of the SNU scholars, Mr. Kim, hcompleted the calibration of capacitance sensors earlier in the spring. Since he had to return to SNU in June, this study is assigned to Mr. Samet Ekinci, a new MS student. Currently, dynamic calibration of capacitance sensors is underway. Data acquisition is expected to start in October 2013.
  2. *Pipe Diameter Effect on Flow Characteristics:* Upscaling is always a relevant subject in multiphase flow in pipes. The 2-in. ID facility has a 3-in. ID horizontal return line. This line will be used to study diameter upscaling in high viscosity oil–gas two-phase flow. This project is assigned to a new SNU Scholar, Mr. Teawoo Kim. Instrumentation of the line is currently underway.
  3. *Oil-Gas Flow Behavior in Upward Vertical and Highly Deviated Pipes:* The objective of this study is to investigate high viscosity oil-gas flow in vertical and deviated wells for a viscosity range of 180 – 587 cp. Modification of TUFFP's 2-in. ID three-phase flow facility has been completed, and most of the instruments have been calibrated. Dynamic calibration of capacitance sensors will be completed soon. After the completion of dynamic calibrations, the data acquisition will resume. Initially, vertical flow configuration will be studied. The signal processing program developed by Brito (2012) has successfully been migrated to Matlab environment and tested using Brito's (2012) data.
  4. *Oil-Gas Flow Behavior in Downward Vertical and Highly Deviated Pipes:* The objective of this study is to investigate high viscosity oil-gas flow in downward vertical and deviated pipes for a viscosity range of 180 – 587 cp. The return line of the facility of the upward vertical and deviated pipes project will be used. The return line has already been instrumented. The data will be acquired simultaneously with the upward flow study. This research assistant of this project is Mr. Sunghoon Chung, a Ph.D. student of SNU.
  5. *Medium Viscosity Oil Study:* Only a few experimental studies for medium oil viscosity (20cP<μ_O<200cP) have been published in the literature. Furthermore, current two-phase flow models are based on experimental data with low and high viscosity liquids. Thus, a need exists of experimental and modeling investigation for medium viscosities in order to characterize the two-phase flow behavior for the entire range of possible viscosities.

     Brito (2012) recently completed an experimental study for horizontal pipe flow. After the completion of high viscosity inclined flow tests, the medium viscosity tests are planned for inclination angles of 2° and +2°.

- *"Upscaling Studies."* One of the most important issues that we face in multiphase flow technology development is the scaling up of small diameter and low pressure results to large diameter and high pressure conditions. Studies with a large diameter facility operated at high pressures would significantly improve our understanding of flow characteristics in actual field conditions. 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. The first TUFFP study to be conducted utilizing the new facility is "Effect of Pressure on Liquid Loading". TUFFP members will discuss the continuation studies at length, and a road map will be established in a separate meeting prior to this Advisory Board meeting. The current progress is given below.

1. *Single-Phase Gas Testing:* The objective is to conduct a study to map out the steady operating envelope of the facility and characterize the base line behavior. Since the last Advisory Board meeting, further single-phase gas tests have been completed to determine the loop characteristics. Several minor modifications in the facility have been identified and implemented.

2. *Effect of Pressure on Liquid Loading:* During this period, studies have been concentrated on finalizing the fine measurement instruments. Wire mesh sensors are being manufactured by HZDR and expected to be delivered to TU in the fall of 2013. The Canty High Pressure Visualization Device is ready for installment on the facility. The iso-kinetic probe device has been purchased and ready for installation into the test section. The placement of all of the instrumentation has been modified to eliminate obtaining non-disturbed flow information. Moreover, the quick-closing valve holdup measurement technique used in other facilities has been modified for this project.

   Mr. Duc Vuong, a Ph.D. student, has successfully passed his Ph.D. qualifying exams. Two-Phase flow testing is expected to start in January 2014.

- *"Effect of MEG on Multiphase Flow Behavior."* TUFFP's 6-in. ID low pressure facility is now being utilized for this project. Currently, Mr. Hamid Karami, a Ph.D. student, is conducting baseline tests with no MEG.

  The entrainment rate measurements were conducted using iso-kinetic probes for water cuts of 60%, 80%, and 100%, and superficial gas velocities of 17, 19, 21, 23 m/s. The acquired data will be used, along with the data of Gawas (2013) for water cuts of 40% and less, to analyze the effects of different parameters on the entrainment behavior of oil and water droplets.

  After completion of the tests without glycol, the next phase of experiments will be conducted for different concentrations of glycol added to the aqueous phase, and testing will be completed with glycol under steady-state flowing conditions.

- *"Liquid Loading of Gas Wells."* Liquid loading in the wellbore has been recognized as one of the most severe problems in gas production. At early times in 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 significantly reduces the gas production rate.

  Although considerable 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 the mechanisms causing the loading.

  Ms. Mujgan Guner recently completed an experimental study for the deviation angle range between 0° and 45°.

  During this reporting period, Mr. Yasser Al-Saadi has completed the experimental part of his study to investigate liquid loading for the deviation angle range between 45° and 90°. With his experimental results, we now have a complete set of liquid loading data for the entire range of deviations. Mr. Al-Saadi has also completed a performance analysis of the existing prediction models and software.

- "*Onset of Liquid Accumulation in Oil and Gas Pipelines.*" Accumulation of liquid, oil and/or water at the bottom of an inclined pipe is known to be the source of many industrial problems, such as corrosion and terrain slugging. Accurate quantification of the required gas velocities to efficiently sweep out the water and prevent accumulation and accurate prediction of oil and water holdup are of great importance. Currently, minimum gas velocity or critical angle requirements, which are often found to be very conservative, are being implemented with various success rates to prevent corrosion in multiphase pipelines.

  An experimental and theoretical modeling project has already been initiated to better quantify the accumulated liquid volumes and the critical gas velocity/inclination angle.

  TUFFP's 3-in. ID three-phase flow facility will be used for the experimental portion of this study after the completion of the liquid loading project. Ms. Yilin Fan, a Ph.D. student, has been assigned to the project. During this period, she has successfully passed her qualifying exams.

- "*Unified Mechanistic Model.*" TUFFP has been maintaining and continuously improving the TUFFP unified model. TUFFP has decided to rewrite the unified model software with an emphasis on modularity and computation efficiency. Significant progress is made in making the software modular. A detailed presentation outlining the progress is given in this brochure.

- *"Three-Inch ID Three-phase Flow High Pressure Facility Development."* Tulsa University High Viscosity Oil Projects (TUHOP) Joint Industry Projects has been completed. An insufficient number of members displayed interest in the continuation of TUHOP. Therefore, a proposal was made to consolidate TUHOP efforts into TUFFP to pursue high viscosity oil multiphase flow research more vigorously. This proposal was unanimously approved by TUFFP Advisory Board and has already been implemented as proposed. The facilities processing center plumbing will be completed by December 2013.

- *"Application of Minimum Energy Dissipation (MED) Concept in Multiphase Flow in Pipes."* The minimum energy dissipation concept postulates that a system stabilizes to its minimum total energy loss. Application of this concept has been found in thermodynamics and simulation of the flow in river systems (open channel flow). Moreover, the concept has recently been applied in the prediction of two-phase flow splitting in parallel pipes. The first successful application of the concept in two-phase flow in pipes was demonstrated by Mr. Hoyoung Lee for stratified gas-liquid flow.

  During this reporting period, a related concept "Equal Energy Dissipation" was successfully applied in flow pattern prediction and interfacial friction factor closure relationship development by Dr. Abdel Al-Sarkhi.

- *"TUFFP Experimental Database Development."* TUFFP has 46 gas-liquid data sets including steady-state and transient experiments. More than 10,000 steady-state data records exist for gas-liquid flow.

  The main objective of this project is to construct a comprehensive multiphase flow database of TUFFP experimental data sets.

  Schlumberger already developed a steady-state multiphase database software using Microsoft Access, which has been donated to TUFFP. This software will be further developed to accommodate the diverse nature of TUFFP's data.

The current TUFFP membership increased to 18 with the addition of DSME. Efforts continue to further increase the TUFFP membership level. A detailed report on membership and financial matters is provided in this report.

Several related projects are underway. The related projects involve sharing of facilities and personnel with TUFFP.

Tulsa University Paraffin Deposition Projects (TUPDP) consortium has successfully completed its fourth three-year phase. A new three-year phase has already been started with seven members.

The Tulsa University Horizontal Well Artificial Lift Projects, TUHWALP, is addressing the artificial lift needs of horizontal wells drilled into gas and oil shales. TUHWALP started its activities in July 2012. The current membership stands at 16. Significant interest in this consortium exists. We anticipate reaching 20 members by the end of 2013. The yearly membership fee is $50,000.

Fluid Flow Projects

81st Fluid Flow Projects Advisory Board Meeting

Welcome

Safety Moment

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

Introductory Remarks

- 81^{st} 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)
  - Eduardo Pereyra (Associate Director)
  - Carlos Torres (Research Associate)
  - Jinho Choi (Research Associate)
  - Abdel Al-Sarkhi (KFPMU – Visiting Research Professor)
  - Eissa Al-Safran (KU – Collaborator)

Team …

- Project Coordinators
  - Linda Jones
  - Kelley Friedberg
- Project Engineer
  - Scott Graham
- Research Technicians
  - Craig Waldron
  - Norman Stegall
  - Don Harris
  - Franklin Birt
- Web Master
  - Lori Watts

Team …

- TUFFP Research Assistants
  - Feras Al-Ruhaimani (Ph.D.) – Kuwait
  - Yasser Al-Saadi (MS) – Saudi Arabia
  - Jon Conner (BS) - USA
  - Samet Ekinci (MS) – Turkey
  - Yilin Fan (Ph.D.) - China
  - Hamid Karami (Ph.D.) – Iran
  - Duc Vuong (Ph.D.) – Vietnam

Team …

- SNU Visiting Research Assistants
  - Sunghoon Chung (Ph.D. Student of SNU)
  - Taewoo Kim (MS Student of SNU)

Guests

- Tod Canty, JM Canty
- Jeff McGhee, JM Canty

Agenda

- 8:30 Introductory Remarks
- 8:45 Progress Reports
  - Low Liquid Loading Three-Phase Flow and Effects of MEG on Flow Behavior
  - 6-in ID High Pressure Facility Single-Phase Flow Tests
  - Pressure Effects on Two-Phase Oil-Gas Low Liquid Loading Flow
- 10:15 Coffee Break

Agenda …

- 10:30 Progress Reports
  - Liquid Loading of Gas Wells with Deviations from 60° to 90°
  - Onset of Liquid Accumulation in Oil and Gas Pipelines
  - TUFFP Experimental Database
  - Unified Model Computer Code - Update

Agenda …

- 12:00 Lunch
- 1:00 Progress Reports
  - Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Pipes
  - Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Downward Flow
  - Effect of Pipe Inclination on Flow Characteristics of High Viscosity Oil-Gas Two-Phase (Revisit)
  - Pipe Diameter Effect on Flow Characteristics for Medium and High Viscosity Oil-Gas Two-Phase Horizontal Flow
- 2:15 Coffee Break

Agenda …

- 2:30 Progress Reports
  - Energy Minimization and Minimum Energy Dissipation Concepts in Multiphase Flow
  - Unified Interfacial Friction Factor for Annular, Churn and Slug Flows
  - TUHOP Incorporation

Agenda …

- 3:45 Business Report
- 4:00 Open Discussion
- 4:15 Adjourn
- 6:00 Reception

Other Activities

- September 24, 2013
  - TUFFP Workshop
  - 6-in. ID – High Pressure Facility Utilization Discussion
  - Facility Tour I
  - Reception
- September 25, 2013
  - Reception
- September 26, 2013
  - TUPDP Meeting

Fluid Flow Projects

Low Liquid Loading Three-Phase Flow and Effects of MEG on Flow Behavior

Hamidreza Karami

Outline

- Introduction
- Objectives
- Comments from Last ABM
- Experimental Program
- Results Without MEG
  - Droplet Entrainment Rate
  - Liquid Holdup
  - Pressure Drop
  - Wetted Wall Fraction
- Modeling Plans
- Future Activities

Introduction

- Low Liquid Loading Flow Influences Different Flow Characteristics
- Very Few Experiments for Large-Diameter Pipes
- MEG is Injected Continuously as Hydrate Inhibitor in Offshore Systems
- Its Impact on Flow Pattern, Holdup, Pressure Drop Predictions is Not Well Understood
- Need to Generate Experimental Data and Improve Model Predictions

Objectives

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

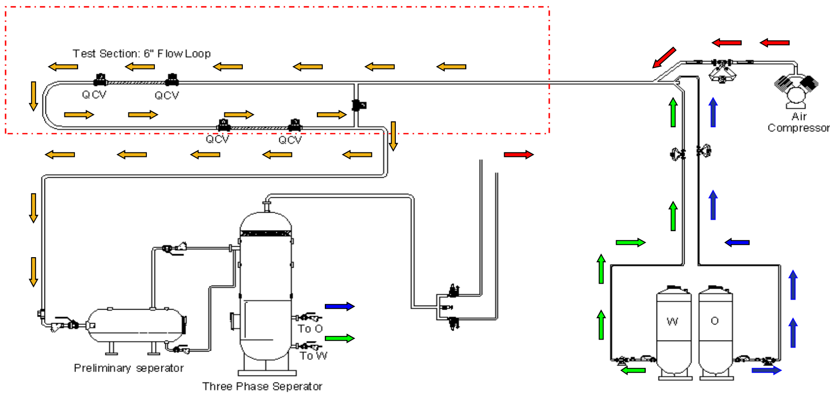
Comments from Last ABM

- Experimental Results to be Repeated: Accepted
- Gas and Liquid Phase Velocity Profiles to Be Measured: Considered for Future Studies
- Wave Characteristic Measurements to be Obtained in Lower v_{SG} values: Accepted
- Entrainment Rate and Wave Characteristic to be Coupled in Modeling: Accepted
- Study to be Linked with Field Condition: Accepted
- Effects of *MEG* on Flow Characteristics to be Analyzed: Accepted

Experimental Program

- Low Liquid Loading Facility Used (6-in. ID)
- Testing Fluids: IsoPar-L Oil, Tap Water, Air, Mono Ethylene Glycol (MEG)
- Tests Under Steady-State Conditions
- Aqueous Phase ρ, μ, σ, … to be Investigated for Different Temperatures and MEG Weight Percentages

Experimental Facility



Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Test Matrix

- Horizontal Cases
  - No Glycol
  - 50% Glycol
- Parameters to Be Investigated
  - Entrainment Rate
  - Liquid Holdup
  - Wave Characteristics
  - Pressure Drop
  - Wetted Wall Fraction

Fluid Flow Projects

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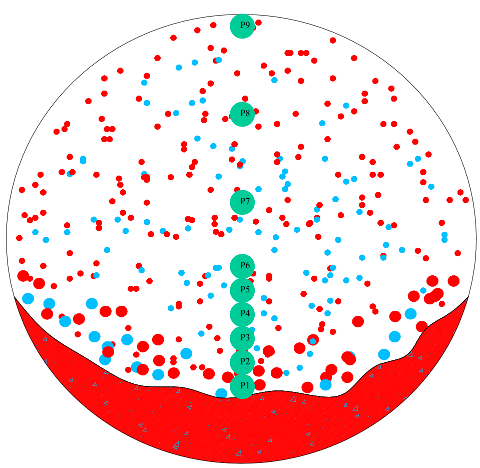
Droplet Entrainment Rate

- **Method: Iso-Kinetic Probe Sampling**
- **Range of Parameters Investigated**
  - v_{SG} : 17, 19, 22.5, 26 m/s
  - v_{SL} : 1, 2 cm/s
  - *WC* : 60, 80, 100%
  - MEG: 0% wt.

Droplet Entrainment Rate …

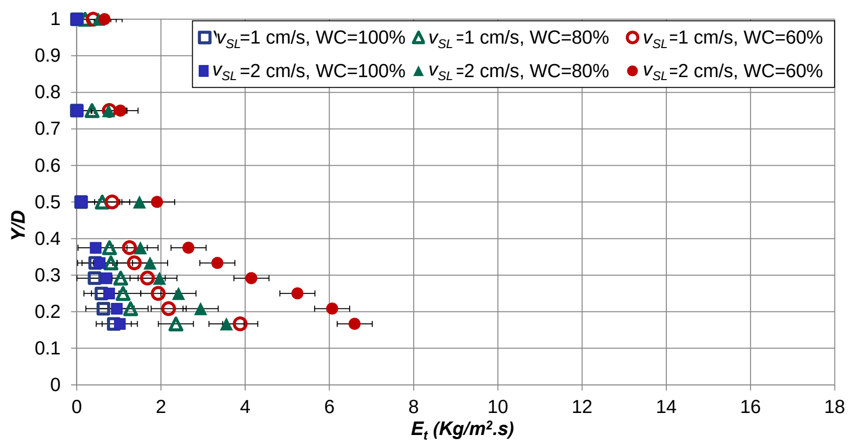
Probe Positions



$$\begin{cases} h_1 = 1'', \\ h_2 = 1.25'', \\ h_3 = 1.5'', \\ h_4 = 1.75'', \\ h_5 = 2'', \\ h_6 = 2.25'', \\ h_7 = 3'', \\ h_8 = 4.5'', \\ h_9 = 6'', \end{cases}$$

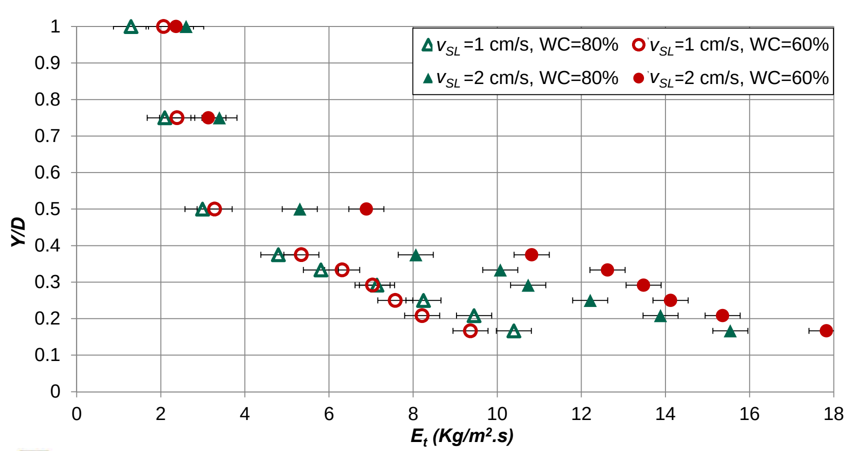
Effect of v_{SL} and *WC* on Entrainment …

v_{SG}=19 m/s



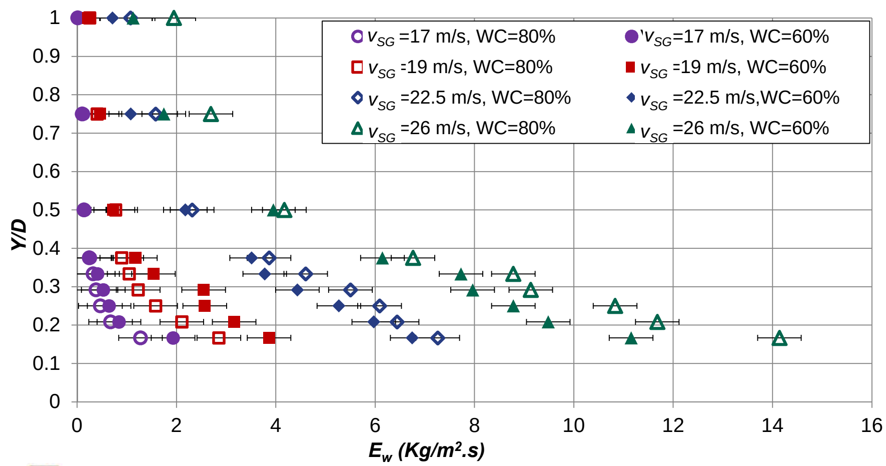
Effect of v_{SL} and *WC* on Entrainment …

v_{SG}=26 m/s



Effect of v_{SG} on Water Entrainment

v_{SL} =2 cm/s



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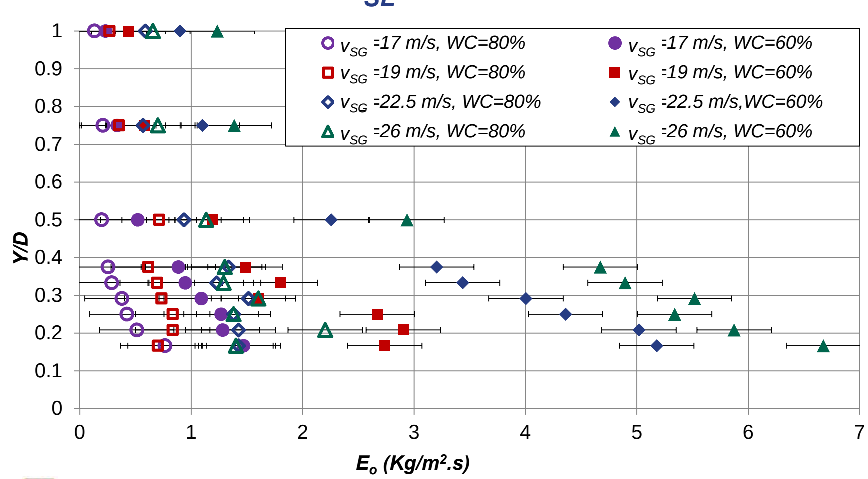
Effect of v_{SG} on Oil Entrainment

v_{SL}=2 cm/s



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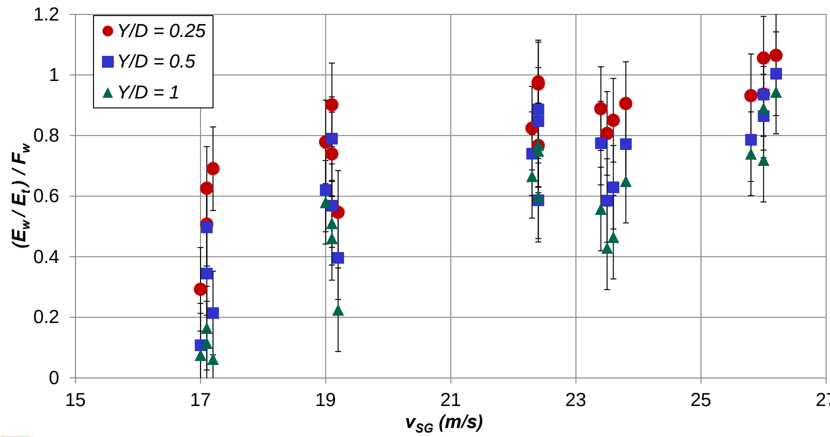
Effect of v_{SG} on Relative Water Entrainment

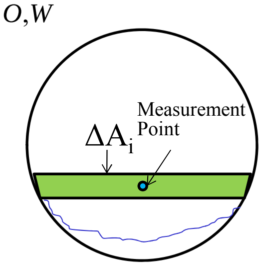
All v_{SL} and WC Values



Droplet Entrainment Fraction

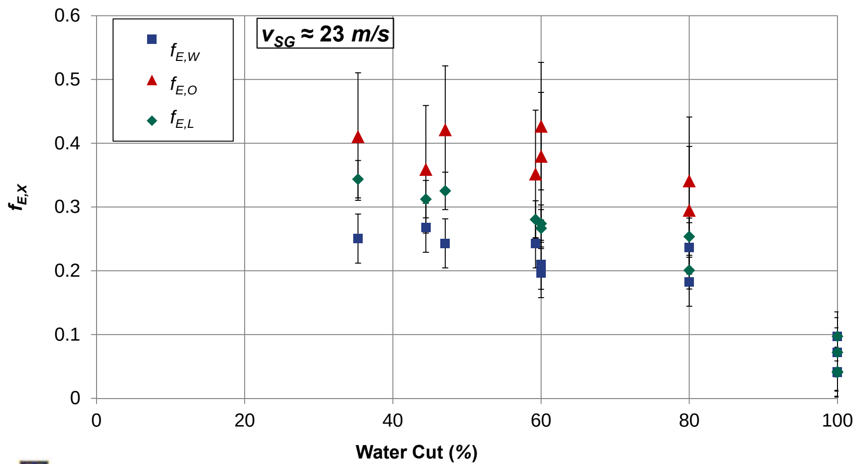
- Estimation through Step-by-Step Integration

$$
\begin{cases}
W_L = W_O + W_W = A_P v_{SL}\left[\rho_W WC + \rho_O (1 - WC)\right] \\
W_{X,E} = \int_{A_P} E_X .dA = \sum_i E_{X,i} .\Delta A_i \qquad , X = L, O, W \\
f_{E,X} = \dfrac{W_{X,E}}{W_X} \qquad , X = L, O, W
\end{cases}
$$



Droplet Entrainment Fraction …

- Water Cut Effect



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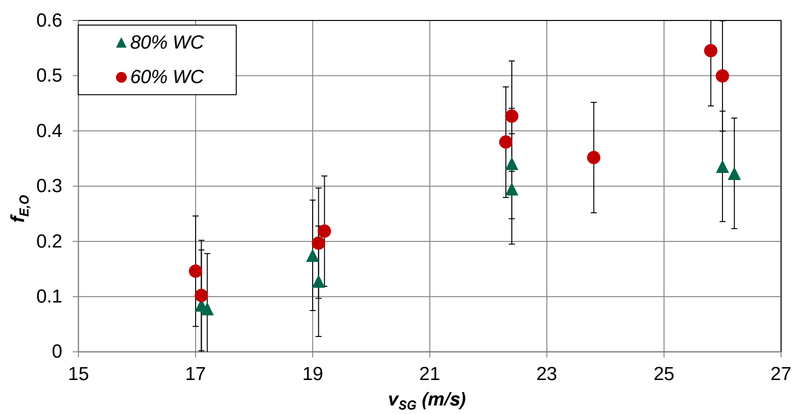
Droplet Entrainment Fraction …

- Oil Entrainment Comparison by v_{SG}



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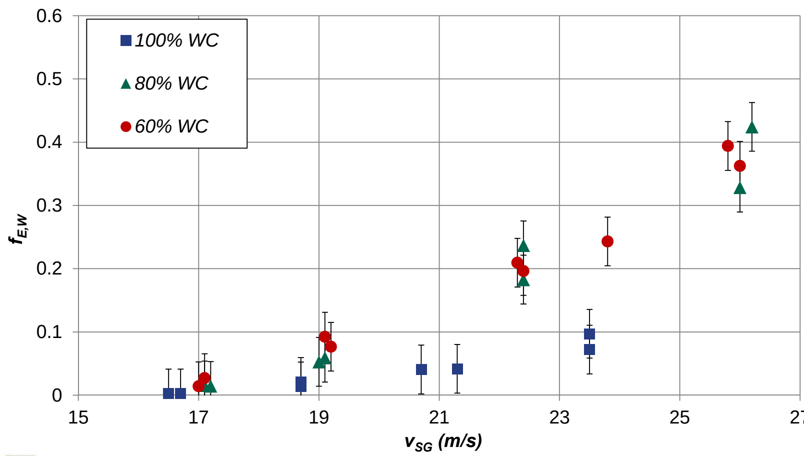
Droplet Entrainment Fraction …

- Water Entrainment Comparison by v_{SG}



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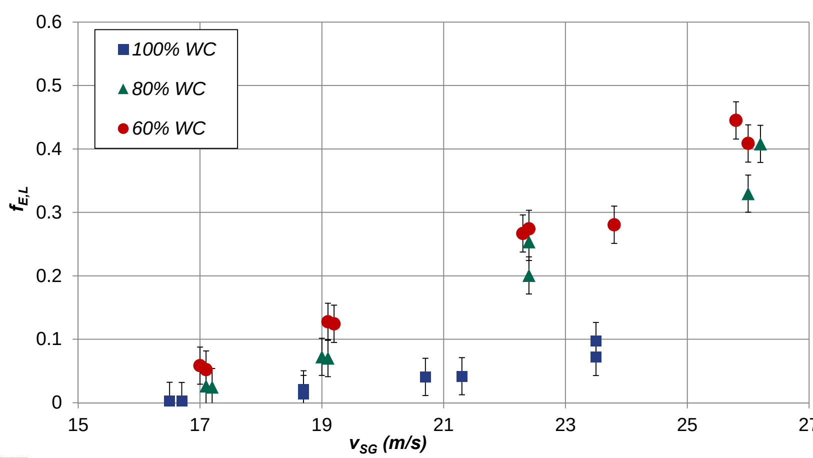
Droplet Entrainment Fraction …

- Total Entrainment Comparison by v_{SG}



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Entrainment Rate Summary

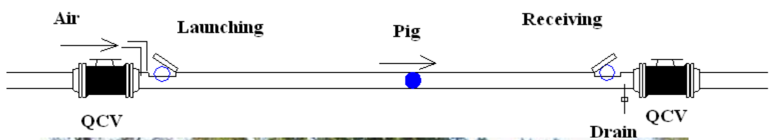
- Slight Increase in Entrainment by Increasing v_{SL} and Decreasing *WC* at Constant v_{SG}
- Entrainment Strongly Dependent on v_{SG}
- Entrainment More Cross-Sectionally Uniform at Higher v_{SG} Values and Water Entrainment Ratio Closer to *WC* Value
- $f_{E,L}$ Increases Significantly as *WC* Decreases from 100% *WC* to Lower Values
- $f_{E,O} > f_{E,L} > f_{E,W}$
- $f_{E,L}$ Values up to Almost 50% Observed at Highest Experimental v_{SG}

Liquid Holdup

- Method: QCVs and a Pigging System
- Range of Parameters Investigated
  - v_{SG} : 9.5, 11.5, 13, 15, 17, 19, 22.5 *m/s*
  - v_{SL} : 1, 2 *cm/s*
  - *WC* : 0, 20, 40, 60, 80, 100%
  - *MEG*: 0% *wt.*
- Overall 96 Data Points
- Unified Model (2012) and Xiao Used for Model Comparison

Liquid Holdup …

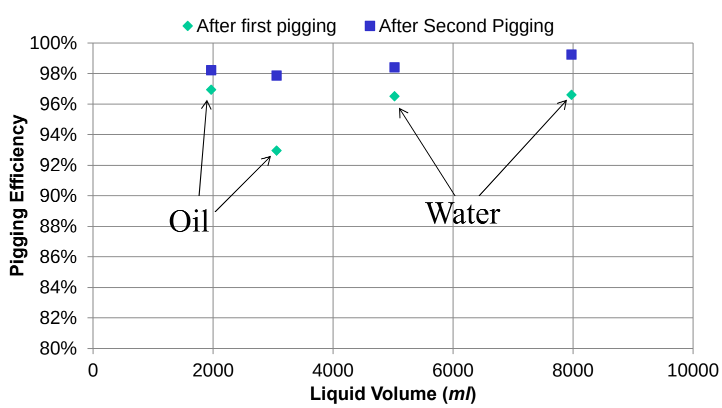
QCVs and Pigging System



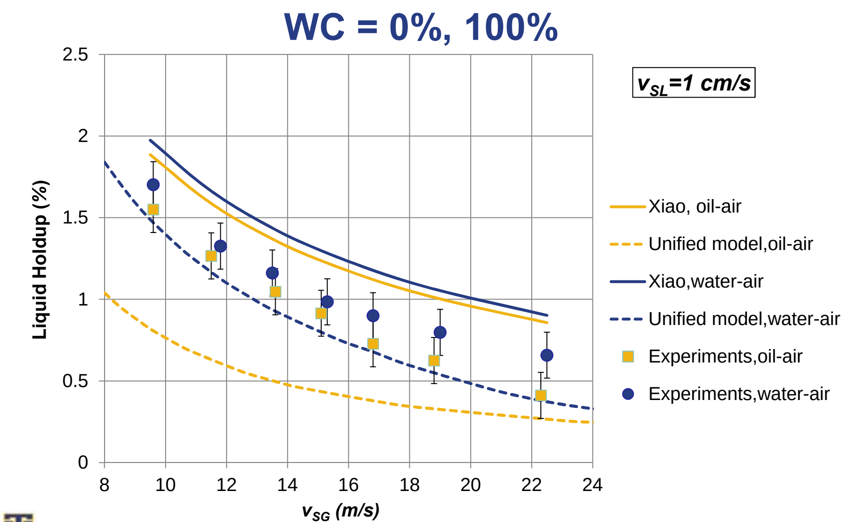
Liquid Holdup …

Pigging System Efficiency

- 100 *ml* Added to All Holdup Readings to Compensate for the Residual Liquid



Effect of v_{SG} on Liquid Holdup



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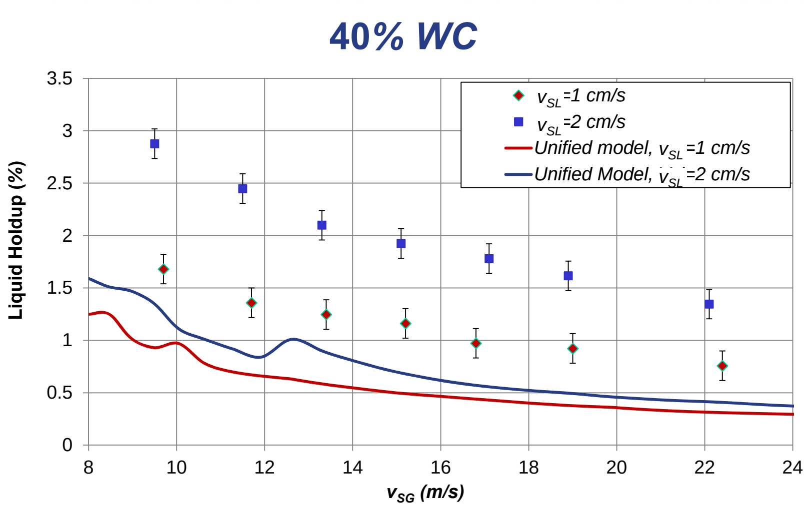
Effect of v_{SG} on Liquid Holdup …



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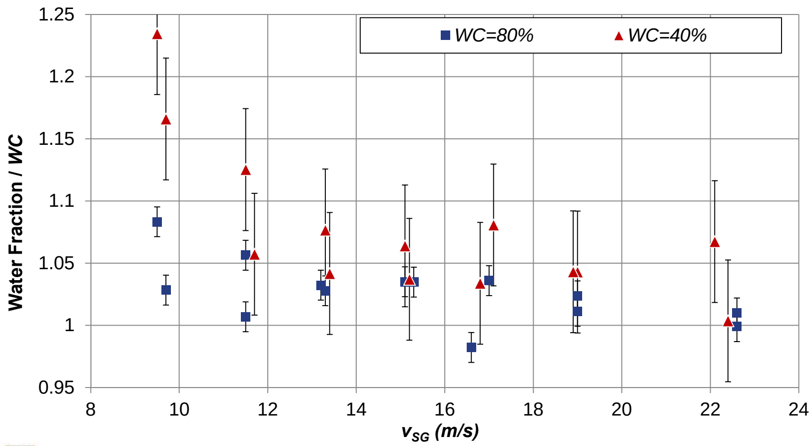
Effect of v_{SG} on Water Holdup Ratio …

- Different Water Cuts



Fluid Flow Projects

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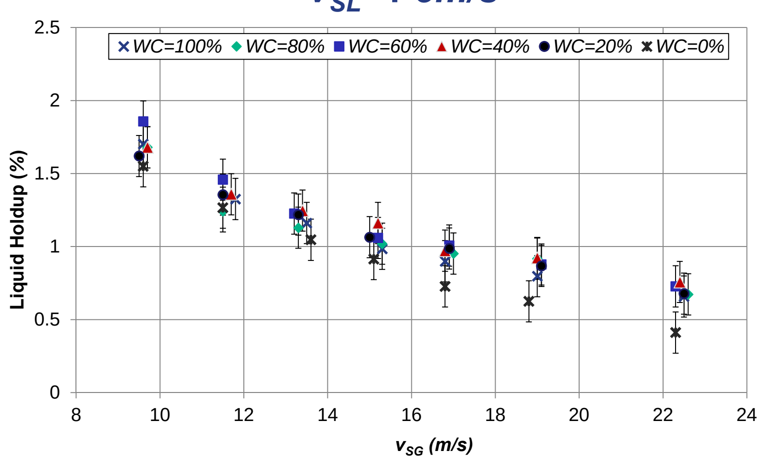
Effects of v_{SG} on Liquid Holdup for Different Water Cuts

v_{SL}=1 cm/s



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Holdup Analysis Summary

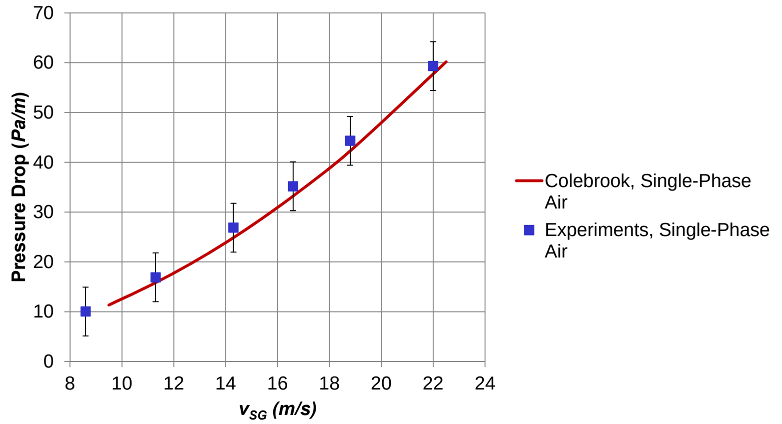
- Increasing Trend by Increasing v_{SL} and Decreasing v_{SG}
  - *WC* Effect Seems Negligible
- Slightly Lower Holdups for Oil-Air Compared to Water-Air
- Xiao and Unified Models Perform Poorly
- Water Holdup Ratio Approaching to Unity by Increasing v_{SG}

Pressure Drop

- Averaging the Readings of 3 Differential Pressure Transmitters
- Range of Parameters Investigated
  - v_{SG} : 9.5, 11.5, 13, 15, 17, 19, 22.5 *m/s*
  - v_{SL} : 1, 2 *cm/s*
  - *WC* : 0, 20, 40, 60, 80, 100 *%*
  - *MEG*: 0% *wt.*
- Overall 96 Data Points

Pressure Drop Verification

- Assumed Absolute Pipe Roughness = 10^{-4} *m*

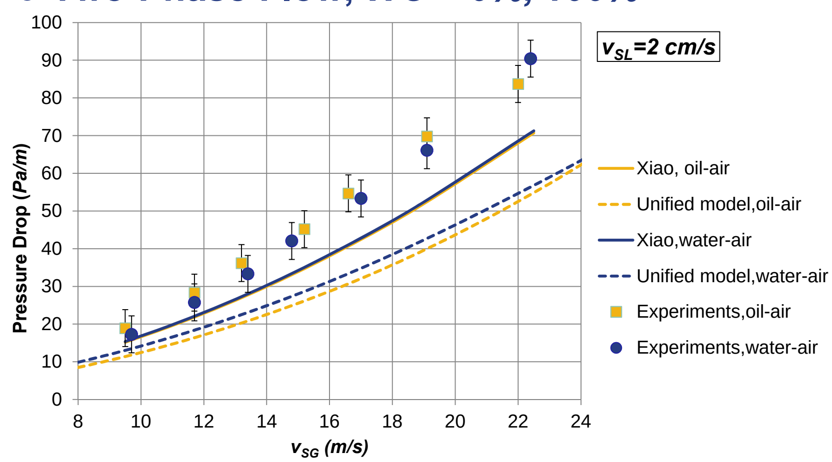


Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Pressure Drop vs. v_{SG}

- Two-Phase Flow, *WC = 0%, 100%*



Fluid Flow Projects

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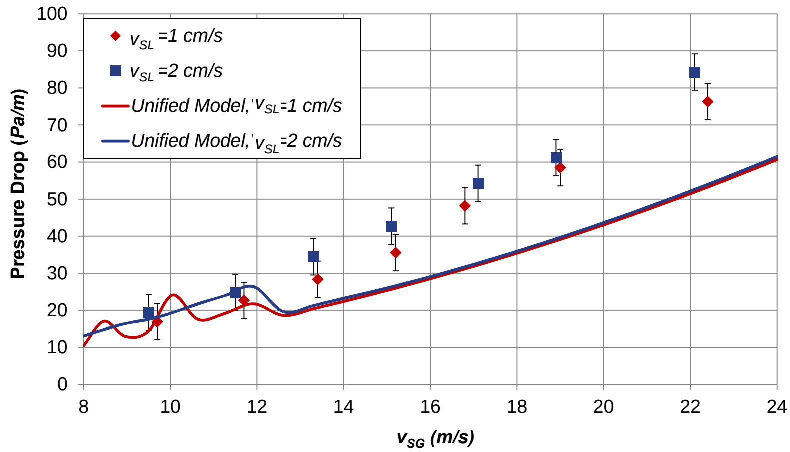
Pressure Drop vs. v_{SG} …

Three-Phase Flow, *WC* = 40%



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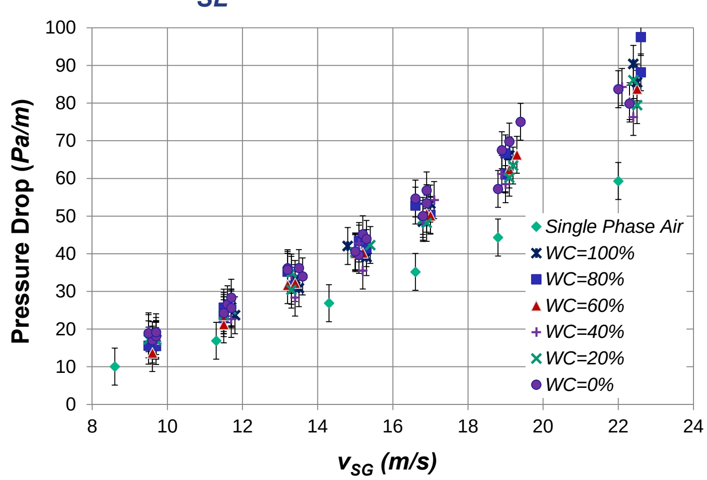
Pressure Drop vs. v_{SG} …

Different v_{SL} and Water Cut Values



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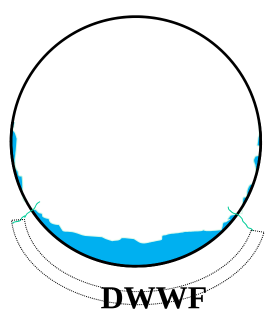
Pressure Drop Analysis Summary

- Water Cut Effects Negligible
- Slight Increase with Increasing v_{SL}
- Gas Phase is Dominant, and Pressure Drop is Strongly Dependent on v_{SG}
- Xiao and Unified Models Consistently Under-Predict

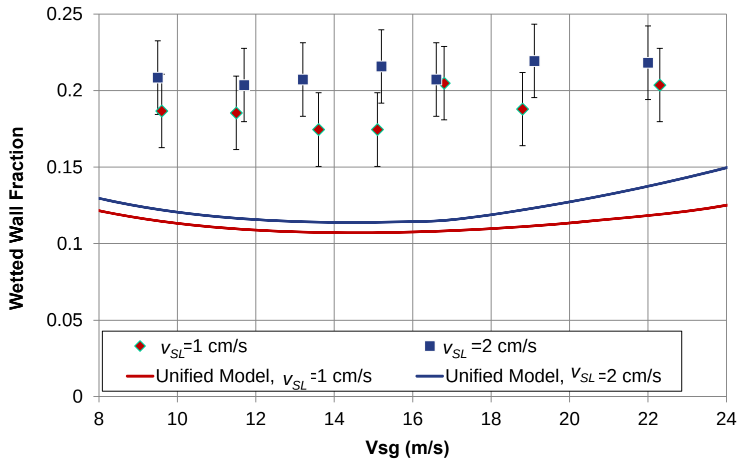
Dynamic Wetted Wall Fraction (DWWF)

- Averaging the Readings of 4 Rulers At Different Positions
- Range of Parameters Investigated
  - v_{SG} : 9.5, 11.5, 13, 15, 17, 19, 22.5 *m/s*
  - v_{SL} : 1, 2 *cm/s*
  - *WC* : 0, 20, 40, 60, 80, 100 %
  - *MEG*: 0% *wt.*
- Overall 96 Data Points



Effect of v_{SG} on DWWF

- Two-Phase Flow, *WC* = 0%



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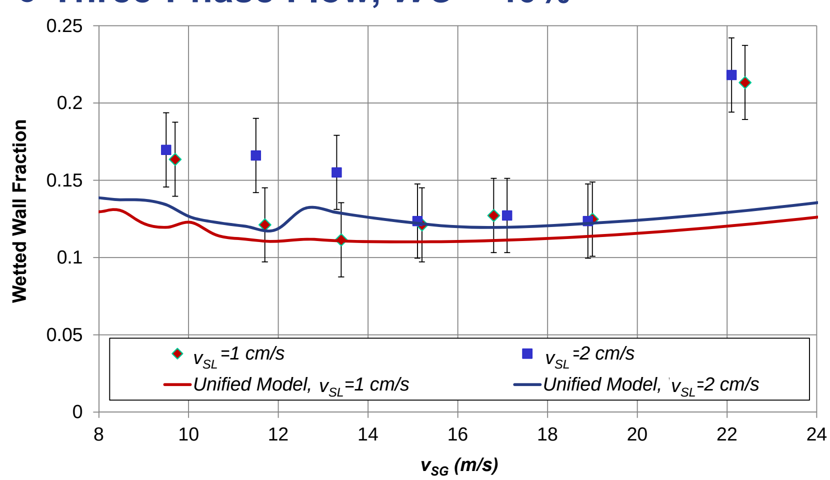
Effect of v_{SG} on DWWF …

- Three-Phase Flow, *WC* = 40%



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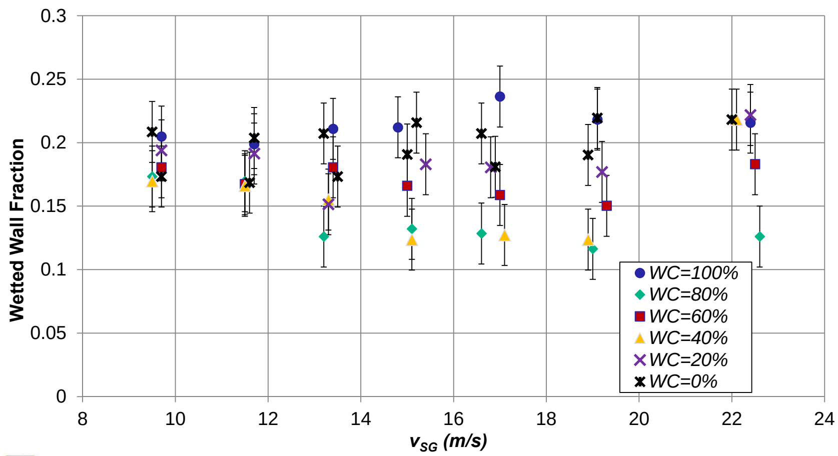
Effect of v_{SG} on DWWF …

- Different Water Cuts (v_{SL}=2 *cm/s*)



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DWWF Analysis Summary

- No Clear Trend Observed
- Slight Increase with Increasing v_{SL}
- Two-Phase Values Slightly Higher than Three-Phase Values

Fluid Flow Projects

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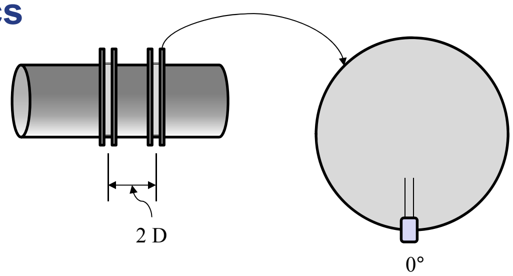
Wave Characteristics

- Conductivity Probes Used for Water/Air
- Effects of Glycol on Wave Characteristics
- Tests Will Be Tried for High Water Cut Three-Phase Flow
- Characteristics
  - Length
  - Celerity
  - Frequency
  - Amplitude

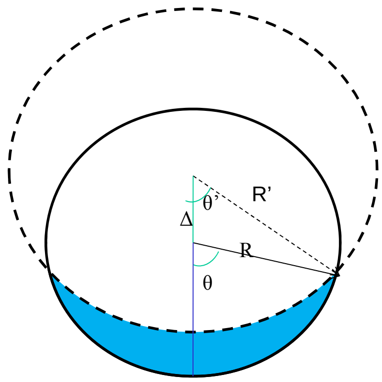


Modeling Preview

- Two-Phase Flow Modeling of Stratified Wavy Flow
  - Watson (1989) Model for Wave and Flow Characteristics: Most Probable Basis
  - An Entrainment Model Considered to Couple with Watson (1989)
- Water-Oil Interactions

Modeling Preview …

- Double Circle Configuration: Geometry of the Model



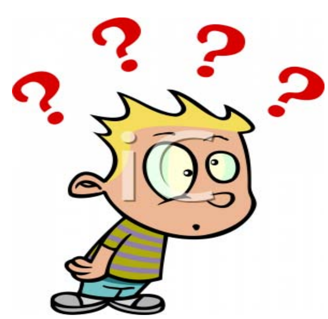
Near Future Activities

- Literature Review (Ongoing)
- Wave Characteristics Measurements (October 2013)
- Experiments with MEG (April 2014)
- PhD Proposal Defense (December 2013)
- Two-Phase Modeling (Spring 2014)

Schedule

Activity	2011			2012												2013												2014											
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Literature Review	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										
Facility Training				■	■	■	■	■	■	■	■	■																											
Facility Preparation													■	■		■			■				■		■														
Test Matrix										■	■	■						■	■						■														
Main Tests																■	■	■		■	■	■		■	■	■	■	■	■										
Additional Tests																														■	■	■	■						
Data Analysis																			■	■		■	■	■			■	■	■	■									
Modeling Study																		■	■			■	■	■		■	■	■	■	■	■	■	■	■	■	■			
PhD Proposal																										■	■												
Dissertation Preparing																																		■	■	■	■	■	
Defense																																							■

Questions and Comments



Three-Phase Low Liquid Loading Flow and Effects of MEG on Flow Behavior

Hamidreza Karami Mirazizi

Project Completion Dates

Literature Review	Ongoing
PhD Proposal Defense	December 2013
Data Acquisition	March 2014
Data Analysis	July 2014
Model Comparison and Development	December 2014

Objectives

The objectives of this study are:

- Acquire flow pattern, holdup, wave characteristics, and entrainment data using a 6–in. ID pipe with and without mono-ethylene glycol MEG under different flow conditions
- Benchmark existing models, document discrepancies
- Propose model improvements if needed

Introduction

One of the most common phenomena in wet gas pipelines is the low liquid loading three-phase flow of gas-oil and water. The presence of these liquids in the pipeline, although in very small amounts, can influence different flow characteristics, such as pressure distribution.

Mono-ethylene glycol (MEG) is used continuously in deep water gas production systems as a hydrate inhibitor. It is injected at the subsea tree upstream of the choke. Some work has been done at The University of Tulsa Hydrates Flow Performance and South West Research Institute on settling and effectiveness of MEG injection under quiescent conditions. However, MEG mixing in multiphase flow and its effect on flow parameters such as liquid holdup, flow pattern, pressure gradient and entrainment rate are not well understood.

Considering the significance of liquid inventory and hydrate management on these large gas tie-backs, there is a need to generate datasets for open literature that can be used by model developers.

In this study, experiments are conducted in a 6-in. ID flow loop. The targeted flow characteristics are the entrainment rate, liquid holdup, wave characteristics, and droplet size distribution. Adopting the Gawas (2013) test matrix, tests are conducted, first without Glycol, and then repeated by adding MEG to the aqueous phase. New experimental data considering MEG effect in multiphase flow behavior will increase the efficacy of production management systems.

Experimental Facility

The flow loop consists of two parallel sections, with 6-in. (0.15 m) ID pipes. Each section is 56.4 m long. Acrylic visualization sections about 8 m long are provided at the end of each section. The inclination angle can change from 0°, horizontal case, to ±2° in inclined case.

IsoPar-L which poses similar properties as wet gas pipelines (low viscosity and specific gravity), is selected for the oil phase. The oil density, viscosity and surface tension at standard conditions are 760 kg/m3, 0.0013 Pa·s, and 0.024 N/m, respectively. In addition, tap water and mono ethylene glycol are forming the aqueous phase, and air is flowing into the test section as the gas phase through two different compressors.

Aqueous phase properties are a function of MEG concentration. The phase density increases slightly with the increase in MEG concentration. However, the change in viscosity is more drastic, and makes the viscosity of the denser phase (aqueous) larger than the oil phase. This may result in different flow characteristics such as the droplet entrainment rate. A portable densitometer, Densito 30PX will be used to confirm glycol concentration in the aqueous phase during the tests. The instrument can measure the density of the aqueous mixture and temperature in an easy and fast manner. The calibration plot will be used every day to back estimate the glycol concentration in the tank.

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. An iso-kinetic sampling system is used to determine droplet flux entrained in the gas phase. The system consists of an iso-kinetic probe, a separator and air flow meter. It can be traversed vertically across the pipe cross section, and the entrainment rate at different positions can be recorded. Two iso-kinetic systems, one foot apart, are used to increase measurement speed. Vertical sampling positions include 9 different spots, ranging from 1 in. away from the bottom, to the top of the section.

Five quick-closing valves (QCV) are used to bypass the flow and at the same time trap the liquid in the test sections. The reaction time of the QCV is less than 1 second. The liquid trapped in the QCV is pigged out with a specially-designed pigging system and is drained into graduated cylinders to measure the oil and water volumes. The system is installed in the testing section with a launching position and a receiving position at each end of the QCV section. An air line with a maximum pressure of 25 psig and adjustable air flow rate is used to push the pig through.

The pigging efficiency tests were carried out to determine the uncertainties. It was realized that around 97% of the liquid is drained after the first pigging, and this number increases to more than 98% after the second pigging. It was decided to add 50 ml. to the experimental readings to account for the remaining liquid in the test section.

Three differential pressure transducers, in the second section of the facility, are calibrated and purged. These transducers are used for recording pressure drop measurements under different flowing conditions, while the liquid holdup measurements are taken.

In order to obtain wetted wall fraction measurements, four different scales are placed on the outer pipe periphery. The average of the readings from these scales gives an approximate estimate of the wetted wall fraction.

A new conductivity system, including multiple conductivity probes around the pipe periphery, is used to measure wave characteristics. Film thickness, wave length, celerity, frequency, and amplitude will be reported for all experimental conditions. These probes are used for two-phase water-air experiments and three-phase experiments with high water cut values, where the water phase is continuous in the liquid film.

Experimental Plan

In order to obtain a comprehensive experimental collection, it was decided to complete the designed test matrix for cases without glycol first, and move to the cases with different glycol concentrations afterwards.

Different flow characteristics including droplet entrainment rate, liquid holdup, pressure drop, wetted wall fraction, and wave characteristics are investigated.

For the test matrix, a major variable is selected to be the superficial gas velocity. It is changing from less than 10 *m/s*, to more than 20 *m/s*. However, the entrainment was not noticeable for v_{SG} values of less than 17 *m/s*. Superficial liquid velocity values of 1 and 2 *cm/s* give a limited capability of looking into the liquid rate effect. Experiments are conducted for all ranges of water cut, including two-phase cases of 0 and 100% water cut, and three-phase cases of 20, 40, 60, and 80% water cut. At this stage, all the experiments are planned for horizontal and steady state conditions.

Preliminary Experimental Results

At this stage, experimental results in entrainment rate, liquid holdup, pressure drop and wetted wall fraction are completed for cases without MEG. They are presented in this section.

Entrainment Rate

The entrainment rate measurements were conducted using isokinetic probes for water cuts of 60%, 80%, and 100% which were not included in the Gawas (2013) study, and superficial gas velocities of 17, 19, 22.5, 26 *m/s*. These data can be used, along with data from Gawas (2013) for water cuts of 40% and less.

After initial analysis of the tests conducted, it can be observed that v_{SG} is the main influential parameter on the entrainment rate. The total entrainment rate seems to increase slightly, by changing v_{SL} from 1 to 2 *cm/s*, and by decreasing water cut from 100 to 60%. However, it increases much more significantly from v_{SG} of 17 *m/s* to 26 *m/s*. Looking at the entrainment rates of oil and water, separately, similar trends can be observed. However, the effect of water cut change, from 60 to 80%, on the oil entrainment rate is seemingly more pronounced.

For higher values of gas superficial velocity, the water ratio in entrained droplets seems to be very close to the water mass fraction in the liquid phase. Of course, going from the bottom to the top of the pipe this ratio decreases, especially for lower v_{SG} values. However, for very high v_{SG} value of 26 *m/s*, the entrainment process is more uniform, and the mentioned ratio is close to the water mass fraction in the liquid stream, even at the positions close to the top of the pipeline.

We can define $f_{E,X}$ as the entrainment fraction of phase *x* in the gas core, considering *x* as liquid, oil or water and calculate this parameter by integrating over the gas core. $f_{E,L}$ seems to increase significantly by going from two-phase, 100% water cut, to lower water cut values. For all three-phase flow cases, $f_{E,O}$ is higher than $f_{E,L}$, and $f_{E,L}$ is higher than $f_{E,W}$. Increasing the v_{SG} value increases the entrainment significantly, and $f_{E,O}$ value reaches higher than 50% for highest v_{SG} value of 26 *m/s* and water cut of 60%. At this condition, $f_{E,W}$ is around 40%.

Liquid Holdup

The liquid holdup measurements were obtained by QCVs and a Pigging System, for 7 different v_{SG} values. Increasing v_{SL} from 1 to 2 *cm/s* resulted in an increase in holdup. However, v_{SG} showed a decreasing effect on liquid holdup. The trends were similar for different water cut values, and the water cut effect seems negligible. However, interestingly for most cases, the liquid holdup of two-phase oil-air flow is lower than the results for all other water cut cases. This is speculated to be due to a lower oil density phase.

The water holdup ratio is defined as the ratio of water fraction in the holdup sample over the water cut in the inlet stream. This parameter can be affected by the flow pattern in the film, which is believed to change by increasing v_{SG}. It is high for lower v_{SG} values, fluctuating around 1.2, but it gets very close to unity for higher v_{SG} cases. This can be an indication that liquid film gets fully mixed for higher gas rate tests.

Pressure Drop

The readings of 3 DP transducers were averaged to estimate pressure drop for the tests conducted. The gas phase seems to be the dominant phase, and v_{SL} and water cut effects on pressure drop readings are negligible. There is a slight increase in pressure drop by increasing v_{SL}, but the increase by going to higher v_{SG} values is much more pronounced. Although water cut does not seem to change anything here, two-phase oil-air cases give slightly higher pressure drop value than all other water cut cases, which is speculated to be consistent with liquid holdup observations. However, v_{SG} effects seem to be much stronger and masks all the other effects.

Wetted Wall Fraction

The readings of 4 ruler scales were averaged to give a rough estimate of wetted wall fraction for the tests conducted. There was no clear trend observed for this parameter. Apparently, different parameters such as liquid holdup decrease, entrainment rate increase, and changing the interface shape are cancelling each other, and a clear trend cannot be observed. However, the wetted wall fraction seems to be slightly lower for three-phase flow cases with different water cuts than for two-phase cases with either water or oil as the liquid phase. This can be due to surface forces in the liquid phase, or an increase in effective viscosity by going to three-phase flow.

Modeling Preview

The objective of the modeling work is to develop a three-phase flow model by combining predictive models on entrainment rate and wave characteristics. However, the efforts will first be focused on two-phase stratified wavy flow. Watson's (1989) mathematical model for roll wave in two-phase flow pipelines will be used as the basis for the modeling. In this model, he neglected entrainment effects. Therefore, an entrainment model will be considered to be incorporated in Watson's model.

For the liquid-gas interface, a double circle model will be adopted. With this configuration, interface can have any shapes, from flat interface to equal film thickness in uniform annular flow. The geometrical equations for this configuration are derived and verified.

Future Work

After completion of the recent experiments, the newly acquired conductivity probes will be utilized to measure the wave characteristics in September 2013. These measurements are initially targeted for water/air experiments, and they will be used later with glycol in the aqueous phase. This will help estimate the effects of change in viscosity of the liquid phase via glycol in wave characteristics. In addition, conductivity probe measurements will be tried for three-phase oil/water/air flow experiments, especially under high water cut and continuous water phase conditions.

After completion of all the tests without glycol, the next phase of experiments is going to be conducted from October 2013 to March 2014. At this stage, different concentrations of glycol will be added to the aqueous phase, and a simplified test matrix will be completed for different flow characteristics, only in the presence of glycol. All the tests are conducted under steady-state conditions with water and glycol homogeneously mixed in the water tank.

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Dong, H.-K.: "Low Liquid Loading Gas-Oil-Water Flow in Horizontal Pipes," M.S. Thesis, U. Tulsa. Tulsa, OK. 2007.

Gawas, K.: "Low Liquid Loading in Gas-Oil-Water Pipe Flow," PhD Dissertation, The University of Tulsa, 2013.

Watson, M.: "Wavy Stratified Flow and the Transition to Slug Flow," Multi-Phase Flow Proceedings of the 4th International Conference. BHRA, 1989, Bedford, UK, pp. 495–512.

Fluid Flow Projects

6-in ID High Pressure Facility Single-Phase Flow Tests

Jon Conner

Advisory Board Meeting, September 25, 2013

Outline

- Objectives
- Facility
- Literature Review
- Single-Phase Calibration
- Summary
- Future Work

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

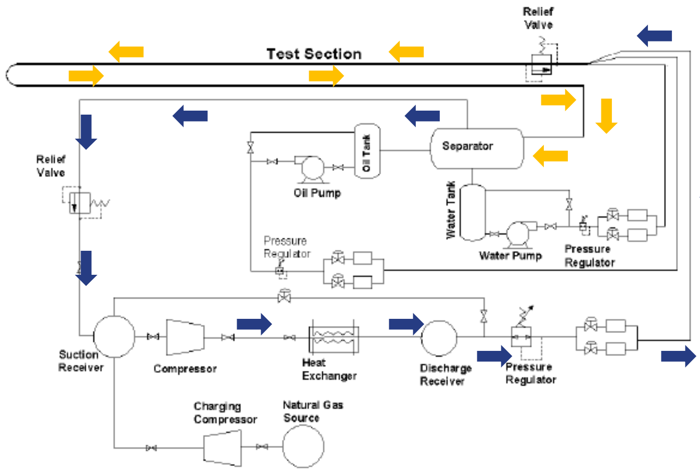
Objectives

- Flow Loop Verification under Single-Phase Conditions
  - Operational Procedure Development
  - Instrumentation and Data Acquisition Testing and Verification
  - Facility Commissioning
  - Pipe Geometry Determination

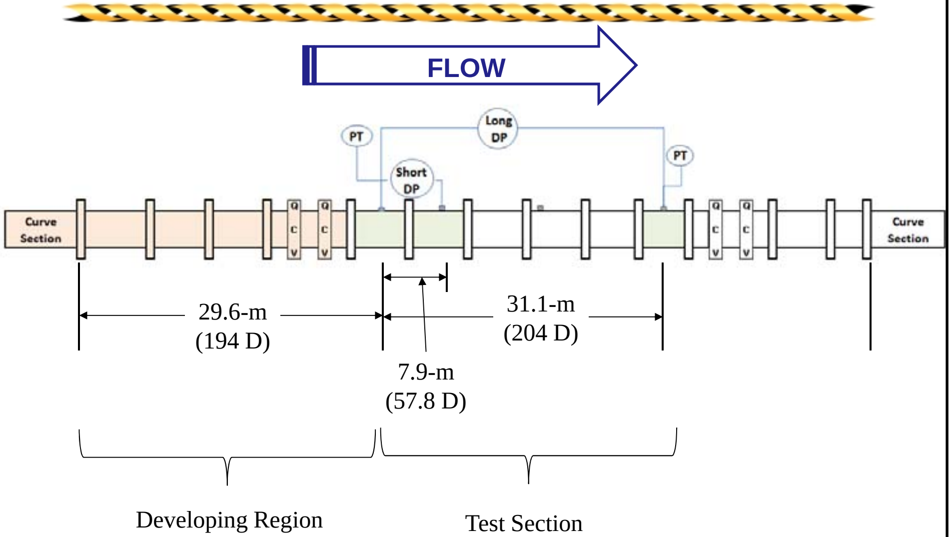
Outline

- Objectives
- Facility
- Literature Review
- Single-Phase Calibration
- Summary
- Future Work

Facility



Facility …



Fluid Flow Projects Advisory Board Meeting, September 25, 2013

Outline

- Objectives
- Facility
- **Literature Review**
- Single-Phase Calibration
- Summary
- Future Work

Literature Review

- Kandlikar *et al.* (2005)
  - Relationship Between Roughness Characteristic Parameters and Fluid Flow Experiments
  - Simple Average Roughness is Unable to Describe the Equivalent Sand-Grain Roughness
  - Suggested Three New Parameters

Literature Review

- Thomas, Grant & Watson (2012)
  - Proposed a Simple Algorithm to Relate Surface Roughness with the Equivalent Sand-Grain
  - Fluid Flow Experiment Showed That the New Algorithm Provides Better Results Than Previous Approaches

Outline

- Objectives
- Facility
- Literature Review
- **Single-Phase Calibration**
- Summary
- Future Work

Single-Phase Calibration

- Pressure Drop is Affected by Fluid Properties, Pipe Diameter and Roughness

$$-\frac{dp}{dx} = \frac{f}{d}\frac{1}{2}\rho\bar{v}^2$$

or

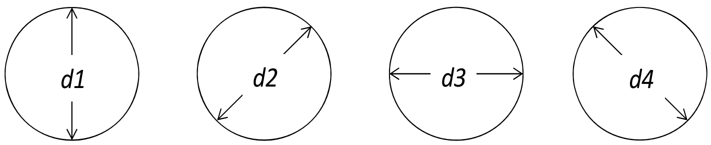
$$-\frac{dp}{dx} = \frac{f}{d^5}\frac{8}{\pi^2}\frac{\dot{m}^2}{\rho}$$

Fluid Properties

- Lookup Table From PVTsim V. 19.0 (Soave-Redlich-Kwong Equation of State)
- Lookup Table Uncertainty was Determined Using Seibt *et al*. (2006) Data
- Systematic Uncertainties
  - Density =0.12-kg/m^3
  - Viscosity =3.95e-7-pa S

Pipe Diameter

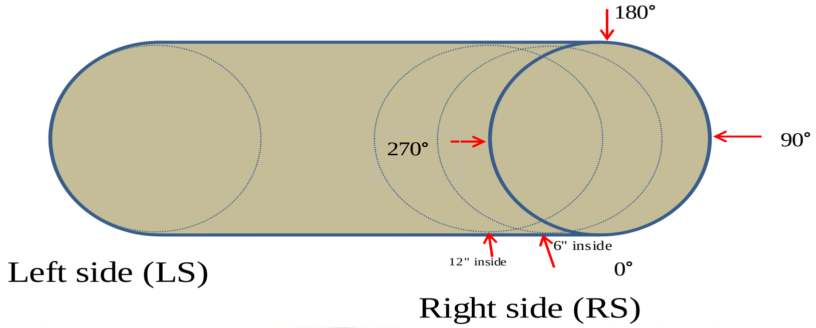
- Diameter is Measured in Three Different Pipe Sections with Caliper
- Four Separate Points at Each Section (12 Diameters Measured)
- Uncertainty (*Ud*) is Calculated Using ISO Model
- *d* = 6.1313 ±0.00714 in. (155.734 ±0.1813 mm)



Pipe Surface Roughness

- Measurement and Results
  - Calculated – Experimental Trials
  - Measured – Roughness Gauge / Profilometer
    - Ra – Arithmetic Mean of Roughness
    - Rq – Mean Square Root of Roughness
    - Rz – Maximum Height

Pipe Surface Roughness



Pipe Surface Roughness

- Mitutoyo Roughness Measurements
- Calculated Roughness vs. Equivalent Sand-Grain Roughness

	Average Roughness [μin]	*U_{95} [μin]*	*U_{95} [%]*	*Corr. Equiv. Sand Grain Roughness [ε]*
Ra	169.87	±3.52	2.07	995.93
Rq	205.82	±4.19	2.04	638.05
Rz	**864.98**	±17.99	2.08	**845.95**

Equivalent Roughness

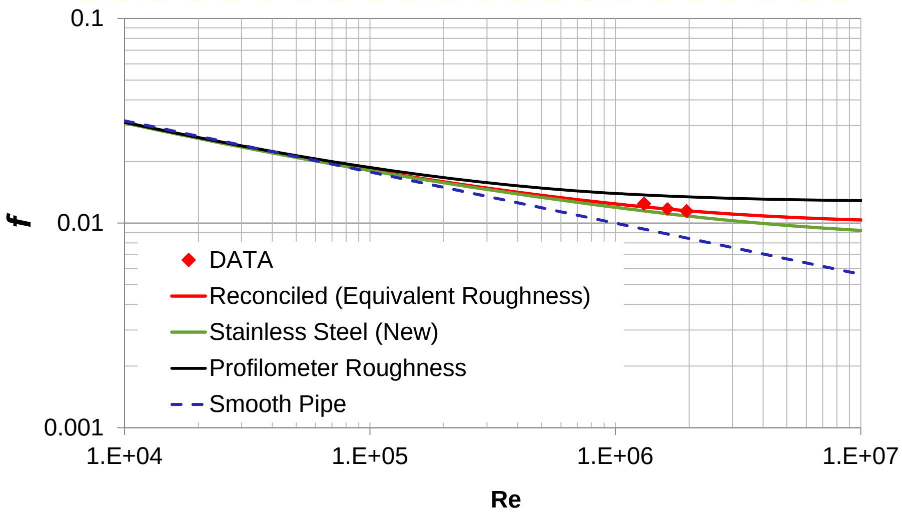
- Langelandsvik *et al.* (2008) McKeon *et al.* (2005) Procedure
  - Friction Factor Calculation

$$f = \frac{\Delta p}{\Delta x}\frac{\pi^2 d^5 \rho}{8\dot{m}^2}$$

  - $\varepsilon/d=3.61x10^{-5}$ from Best Fitting with Colebrook Equation

$$\frac{1}{\sqrt{f}} = -2.0\,Log\left(\frac{\varepsilon/D}{3.7}+\frac{2.51}{\mathrm{Re}\sqrt{f}}\right)$$

Equivalent Roughness



Outline

- Objectives
- Facility
- Literature Review
- Single-Phase Calibration
- **Summary**
- Future Work

Fluid Flow Projects
Advisory Board Meeting, September 25, 2013

Summary

- Developed
  - Standard Operational Procedure
  - Post Processing Test Data Macros
- Inner Pipe Diameter Determination d=6.1313±0.00714 in. (155.734 ±0.1813 mm)
- Profilometer Roughness

Fluid Flow Projects
Advisory Board Meeting, September 25, 2013

Summary

- Fluid Properties
  - U_ρ= 0.12-kg/m^3
  - U_μ= 3.95x10^{-7}-Pa s
- Equivalent Roughness (ε/d=3.61x10^{-5})

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Outline

- Objectives
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- **Future Work**

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Future Work

- Uncertainty Analysis
- Profilometer Roughness Equivalence
- Gas Temperature Control System Implementation
- Single-Phase Runs for Different Pressure Levels
- Flanges Pressure Loss Characterization

Questions/Comments

Six-Inch ID High Pressure Facility Single-Phase Flow Tests

Jon Conner

Project Completion Dates

Standard Operational Procedure	Completed
Delta-V Post-Processing Data Macros	Completed
Nitrogen Properties Lookup Table	Completed
Inner Pipe Diameter Determination	Completed
Pipe Roughness Determination (Profilometer)	Completed
Pipe Roughness Determination (Fluid Flow Experiments)	October 2013
Flange Effect	December 2013
Final Report	December 2013

Objective

The main objective of this project is the flow loop verification under single-phase condition. Some specific objectives are:

1. Develop flow loop operational procedure.
2. Instrumentation and data acquisition testing and verification.
3. Facility commissioning.
4. Pipe properties (diameter and roughness).

Introduction

Studies of single-phase pressure drop in pipes have been in professional literature since the 18th century. It is well accepted that the pressure drop in single-phase pipe flow is a function of flow rate, fluid properties (density and viscosity), pipe diameters and surface roughness. In general, the roughness values reported in the literature do not correspond to any direct measurement using profilometers. The values from profilometers would give an idea of the pipe roughness that could correspond to a back calculation (of roughness) from fluid flow experiments.

Kandlikar *et al.* (2005) carried out an experimental program to determine a roughness characteristic parameter which provides the best agreement with fluid flow experiments. The authors concluded that the simple average roughness was unable to describe the equivalent sand-grain roughness. A surface with many deep pits but is otherwise smooth could have similar average roughness values to a surface with low uniform roughness (i.e. sandpaper). Theauthors suggested three new parameters, proposing that further experimental data is needed to determine the most suitable one.

Recently, Adams and Watson (2012) proposed a simple algorithm to relate surface roughness with the equivalent sand-grain roughness. Fluid flow experiments showed that the new algorithm provided better results than previous approaches.

As can be seen, no consensus is achieved for the determination of the relationship between the roughness parameters and equivalent sand-grain roughness, especially when other elements such as flanges are also incorporated.

Therefore, this study will attempt to characterize the equivalent sand-grain roughness from fluid experiments. Two differential pressure transducers containing different numbers of flanges have been implemented. Equivalent roughness of the pipe is determined by back calculation as shown by Langelandsvik *et al.* (2008) and McKeon *et al.* (2005). Roughness characterizations from this study will be utilized in future multiphase flow experiments.

Facility Description

The new high pressure facility is equipped to operate with three-phase flow (gas, oil and water). This specific project is focused only on the gas system of the new loop. A turbine compressor boosts the pressure of the single-phase gas, which flows through the metering system before reaching the test section. Gas flow rate is controlled through a bypass system. Gas temperature can be controlled above ambient temperature. The system has been designed to reach a maximum gas rate of 18 MMscfd at 450 psi.

Test Section

The stainless steel Schedule 40 inclinable test section has a length of 256 ft and internal diameter of 6 in. The last section can be inclined 3° downward. For upward flow studies, the direction of the flow will be reversed. Thus, the fluid can circulate clockwise and counter-clockwise. Each pipe section between two flanges is equipped with 1/2“ NPT for the connection of differential pressure transducers. Two sets of quick-closing valves are connected on each extreme of the test section and two differential pressure transducers are connected between, namely, a short and long pressure transducer. The long pressure transducer is an open capillary type connected 102 ft apart while the short pressure transducer is connected 26 ft apart. The developing region is 194 ft (380 D). There is one flange between the two legs of the short differential pressure transducer and five between the connections of the long transducer. The difference between numbers of flanges will help in the determination of flange effect over pressure drop.

Over this period the standard operational procedure of the facility has been developed as well as a program to extract the raw data from the Delta V data acquisition system.

Single-Phase Calibration

As mentioned before, the pressure drop in single-phase flow is a function of flow rate, fluid properties (density and viscosity), pipe diameters and roughness. Proper characterization of each parameter needs to be carried out for the equivalent sand-grain surface determination. The mass flow rate is measured by a Coriollis flow meter, while the fluid density and viscosity are determined based on local pressure and temperature using the lookup table method described next.

Nitrogen Properties Lookup Table

The nitrogen (N2) density and viscosity are determined from a lookup table. The properties table has been generated by PVTsim v.19.0 using the Soave-Redlich-Kwong (SRK) equation of state. A matrix of 20 pressure points between 100 and 600 psi and 20 temperatures from 0 to 60° C have been considered. Data Fit v.2.0 has been used to generate a surface over PVTSim data. The final surface has been implemented in a VBA code to be used in Excel applications. The performance of the final VBA routines is compared with the experimental data reported by Seibt *et al.* (2006). The uncertainties are calculated using systematic uncertainty for calibrations proposed by Dieck (2007), yielding a systematic uncertainty of 0.12-kg/m^3 and 3.95E^{-7}-Pa/s for the density and viscosity, respectively. Additional uncertainty is attributed to the gas impurities which are not accounted for in this study. The random uncertainty is determined by the standard deviation of the calculated density in every time step.

Pipe Diameter

The inner pipe diameter is determined by selecting three different pipe sections (randomly selected). For each section, the inner diameter is measured in four points with a caliper. Each measurement is carried out every 45°. A total of 12 diameter measurements have been acquired. The uncertainty (U_d) is calculated using ISO model reported by Dieck (2007). As a result, the average diameter is d=6.13125 ± 0.00714 in (155.7338 ± 0.1813 mm) considering a confidence level of 95%. The diameter uncertainty corresponds to 0.12% of the average diameter which differs from the nominal pipe diameter (6.07 in or 154.178 mm) by 0.06125 in (1.56 mm).

Pipe Roughness Determination (Profilometer)

The instrument used in our experiments was the Mitutoyo Surftest SJ-210, a surface roughness measuring tester. The SJ-210 is a stylus type of instrument, measuring a material's surface as it makes its horizontal pass. Its major components are the drive unit, connecting acquisition cable, and the stylus detector. Three surface parameters have been considered, namely, average roughness (*Ra*), root mean square deviation (*Rq*) and maximum height (*Rz*) of the roughness profile. Utilizing the correlation by Adams and Watson (2012) we obtained a roughness value from *Rz* of 864.98 ± 17.99 μin (21.97 ± 0.4569-μm) with a 95% confidence level. This value, when applied to the Adams and Watson correlation, gave us a value for equivalent sand-grain roughness of 845.95 μin (ε/d= of 1.38 x 10^{-4}).

Pipe Roughness Determination (Fluid Flow Experiments)

Many aspects of the Moody diagram are currently being re-examined. Langelandsvik *et al.* (2008) and McKeon *et al.* (2005) have worked on this issue proposing a procedure to determine the average roughness from pressure measurements and its impact on the Moody diagram and Colebrook equation. In this study, this procedure is used resulting in equivalent roughness (ε/d= 3.61x10^{-5}). As can be observed, there is an order of magnitude difference with our results and Adams and Watson's (2012) correlation. Closer values can be observed if only Ra (ε/d= 2.77 x 10^{-5}) and Rq (ε/d= 3.36 x 10^{-5}) are considered. Further research will be carried out in the coming periods to improve the uncertainty in the acquired data and clarifying this difference.

Future Work

The following future activities will be carried out for this project:

- Pipe Roughness Determination (Fluid Flow Experiments) Oct. 2013
- Flange Effect Dec. 2013
- Final Report Dec. 2013

References

Adams, T., Grant, C., and Watson, H. (2012). “A Simple Algorithm to Relate Measured Surface to Equivalent Sand-grain Roughness,” International Journal of Mechanical Engineering and Mechatronics. v. 1, i. 1. p. 66-71.

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Fluid Flow Projects

Pressure Effects on Two-Phase Oil-Gas Low Liquid Loading Flow

Duc Vuong

Outline

- Objectives
- Previous Meeting Discussion
- Facility Update
- Future Work

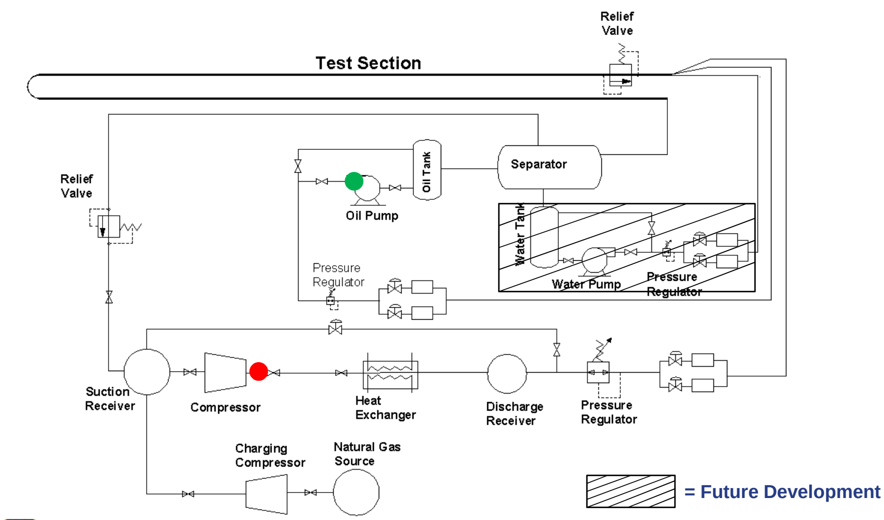
Objectives

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

Previous Meeting Discussion

- Pipe ID Measurement
  - ID = 6.131 ± 0.034 in.
- Roughness Measurement
  - Conner's Results
- Long Term
  - Discussed Yesterday

Facility



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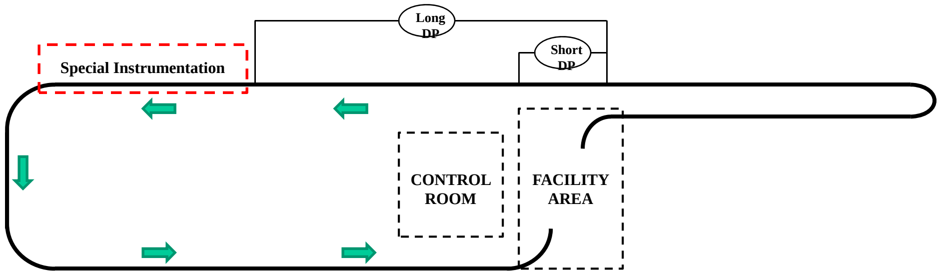
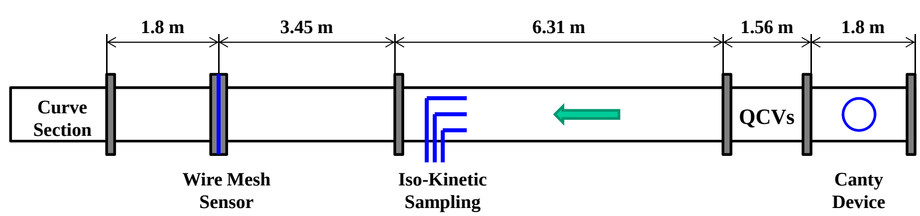
Advisory Board Meeting, September 25, 2013

Facility …





Fluid Flow Projects

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Special Instrumentation

- **Canty Tubular System**
  - Visual Observation, Flow Pattern, and Wetted Perimeter
- **Holdup Measurement QCVs**
  - Liquid Holdup
- **Iso-Kinetic Sampling**
  - Entrainment
- **Wire Mesh Sensor**
  - Flow Pattern, Wave Characteristic, and Wetted Perimeter

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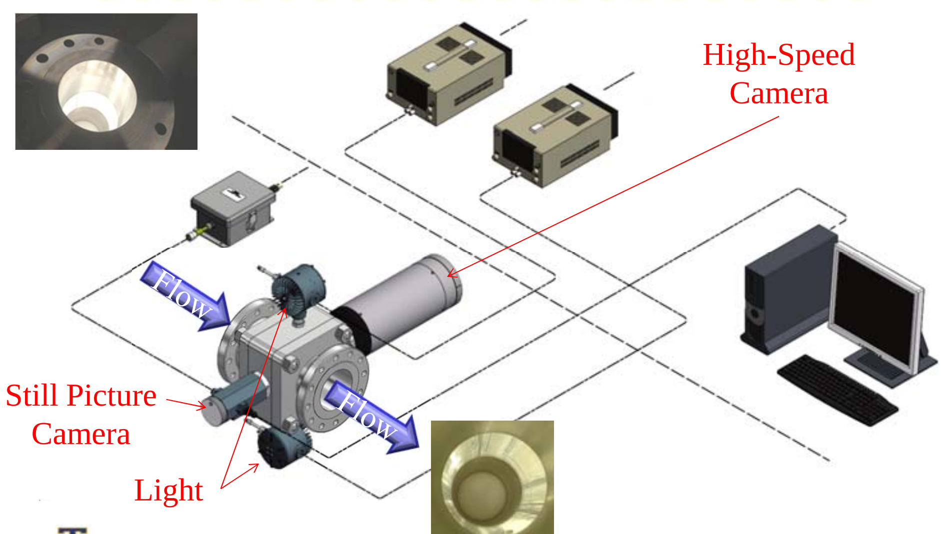
Canty Tubular System



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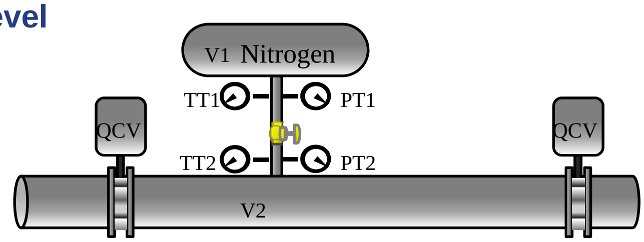
Canty Tubular System …

- Calibration
  - Optimize Camera Location and Light Source to Have Best Quality Picture
  - Calibrate to Measure Wetted Wall Perimeter
- Current Status
  - Ready to Install

Holdup Measurement QCVs

- Principle
  - Equalization of Pressure Between Two Tanks
  - Two-Wire Capacitance Sensor for Oil-Water Level



$$\frac{P_1V_1}{T_1} + \frac{P_2V_2}{T_2} = \frac{P_3(V_1+V_2)}{T_3} \longrightarrow \text{Liquid Holdup} = \frac{V_{QCV} - V_2}{V_{QCV}} \times 100\%$$

Holdup Measurement QCVs …

- QCVs Reaction Time Using High-Speed Camera

	1st [s]	2nd [s]	3rd [s]	Avg.	U [s]
QCV 1	0.352	0.337	0.362	0.350	0.032
QCV 2	0.344	0.341	0.365	0.350	0.033
QCV 3	0.294	0.293	0.302	0.296	0.013
QCV 4	0.351	0.329	0.326	0.335	0.034
QCV 5	0.347	0.350	0.354	0.350	0.010
QCV 6	0.343	0.347	0.337	0.342	0.013
QCV 7 (By Pass)	0.445	0.433	0.483	0.454	0.065

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Holdup Measurement QCVs …

- Estimated Uncertainty Due to QCVs Reaction Time on Holdup Measurement (Worst Scenario)

$$\frac{\Delta Volume}{QCVs\ Volume} = \frac{V_L A_L \Delta t}{L A_P} = \frac{V_{SL} \Delta t}{L} \sim \frac{(0.1\ m/s)(0.04\ s)}{1.56\ m} \sim 0.25\%$$

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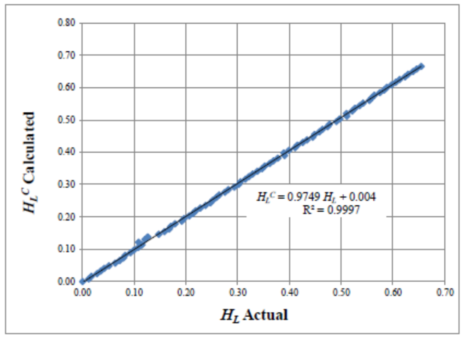
Holdup Measurement QCVs …

- **Calibration**
  - For a Known Liquid Holdup, Perform Holdup Measurement Using Gas EOS Principle
  - Repeat for Different Holdup to Obtain Calibration Curve
- **Current Status**
  - Completed Basic Design
  - Calibration in Fall 2013



Guner (2012) Holdup Measurement Calibration Curve

Fluid Flow Projects

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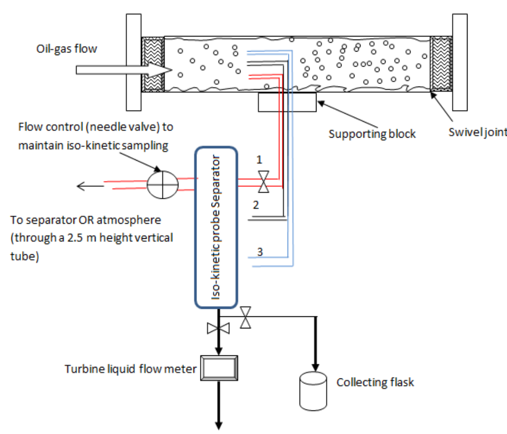
Iso-Kinetic Sampling

- **Principle**
  - Multiple Probes and Swivel Joint Design to Sample Multiple Location
  - Flow Control to Maintain Iso-Kinetic Sampling
- **Calibration**
  - Factory Calibration



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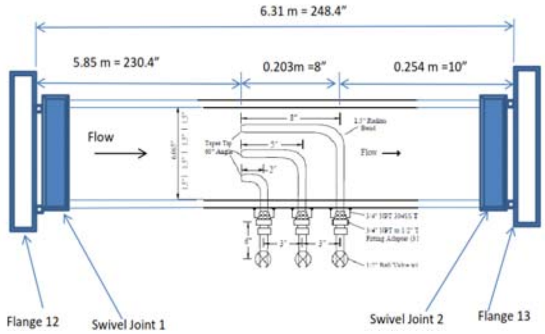
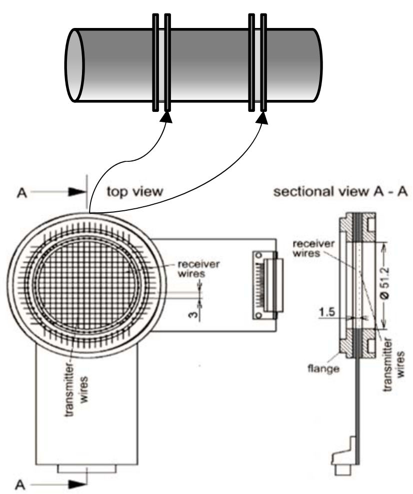
Iso-Kinetic Sampling …

- Current Status
  - Ordered Nozzles and Parts
  - Assembly and Test in Fall 2013



Wire Mesh Sensor

- Principle
  - Electrical Wires Measure the Conductivity or Permittivity of the Fluids
  - Different Electrical Properties Between Oil, Water and Gas
  - Two Consecutive Sensors for Phase Velocity Measurement



Wire Mesh Sensor …

- Calibration
  - Factory Calibration to Test Fluids
  - Verify with Falling Film in Vertical Pipes or with Liquid Droplet on the Grids
- Current Status
  - Ordered from HZDR
  - Pressure Rated to Over 1000 psi
  - Will Be Delivered and Evaluated in Late Fall 2013

Near Future Work

- Completion Dates

Gas Single Phase Test	Sep. 2013
Holdup Measurement System	Dec. 2013
Wire Mesh Sensor	Dec. 2013
Iso-Kinetic Sampling	Dec. 2013
Facility Commissioning	Jan. 2014
Low Liquid Loading Tests	Fall 2014

Research Schedule

Activity	2013								2014												2015				2016			
	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Literature Review	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Qualifying Exam		■	■	■																								
Facility Preparation						■	■	■																				
Facility Commisionning								■	■																			
Main Tests										■	■	■	■	■	■	■	■	■										
Data Analysis											■		■		■		■		■				■					
Additional Tests																					■	■						
Modeling Study																		■	■	■	■		■	■	■	■	■	
PhD Proposal																								■				
Dissertation Preparing																											■	■
Defense																												■

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Questions/Comments

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Pressure Effects on Two-Phase Oil-Gas Low Liquid Loading Flow

Duc Vuong

Project Completion Dates

Literature review	Ongoing
Facility Preparation	November 2013
Preliminary Tests & Instrumentation Calibration	January 2014
Low Liquid Loading Tests	September 2014
Data Analysis and Model Comparison	January 2015
Additional Tests	May 2015
Model Development	September 2016
Final Report	December 2016

Objective

The 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

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

Tulsa University Fluid Flow Project (TUFFP) has been constructing a new high pressure and large diameter pipe facility. The new facility will be first used to study the effects of pressure on two-phase gas-oil flow. Experimental results from this facility will help evaluate and improve the available models and correlation.

Facility Update

This section reports the progress made in construction of the facility since the last Advisory Board Meeting.

Gas single-phase tests were conducted to estimate the pipe roughness before installing special instrumentation. Special instrumentations are being custom built. They will be calibrated and installed into the flow loop. The current status of special instrumentations is briefly summarized as follows:

- **Canty Device:** the device is ready to install into the loop
- **Quick-Closing Valves Holdup Systems:** basic design is completed. QCVs will be modified in-house, then calibration will be performed in Fall 2013.
- **Wire Mesh Capacitance Sensor:** the design drawing is completed. It is being built by HDZR. The system will be installed and evaluated in Fall 2013
- **Iso-Kinetic Sampling:** Iso-kinetic sampling nozzles were completed by Jonas Inc. The system will be assembled and evaluated in Fall 2013.

Experimental Program

Fan (2005) conducted an experimental study on low liquid loading gas-liquid two-phase flow in the 6-in flow loop at low pressure condition. The superficial gas velocity ranged from 7.5 to 21 m/s and the superficial liquid velocity ranged from 0.005 to 0.05 m/s. In order to study the effect of high pressure and large scale pipe diameter on low liquid loading gas-oil two-phase horizontal flow, the same sets of gas and liquid superficial velocities as Fan (2005) are proposed. The tests will be conducted at various different system pressure conditions, specifically 250, 325 and 450 psia.

Isopar L mineral oil is selected as the liquid phase due to its low viscosity and low specific gravity which are similar to properties of a typical gas condensate. The gas phase is nitrogen due to its relatively low safety risk.

The main parameters to be investigated in this study and the associated instrumentations are as follows:

- Pressure Gradient
  - Differential Pressure Transducer
- Flow Patterns and Visual Observation
  - Canty Tubular System
  - Wire Mesh Capacitance Sensor
- Wetted Perimeter
  - Canty Tubular System
  - Wire Mesh Capacitance Sensor
- Liquid Holdup
  - Holdup Measurement QCVs
- Wave Characteristics
  - Wire Mesh Sensor

- Droplet Entrainment
    - Iso-Kinetic Sampling

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.

Future Work

The future tasks for the next period are listed below:

- Literature review
- Facility preparation
- Instrumentation calibration
- Preliminary tests

References

Fan, Y.: "An Investigation of Low Liquid Loading Gas-Liquid Stratified Flow in Near-Horizontal Pipes.", Ph.D. Dissertation Univ. of Tulsa, Tulsa, 2005.

Fluid Flow Projects

Liquid Loading in Deviated Pipes From 60° to 90°

Yasser Alsaadi

Outline

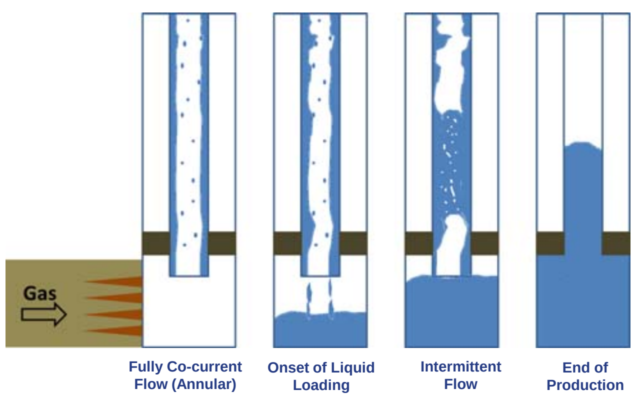
- Objectives
- Introduction
- Literature Review
- Experimental Study
  - Experimental Test Program
  - Experimental Results
  - Model Comparison and Development
- Conclusion and Future Tasks

Objectives

- Study the Onset of Liquid Loading in Deviated Pipes from 60° to 90°
- Investigate the Effect of Highly Deviated Angles on Liquid Loading
- Compare Experimental Results with Existing Models
- Improve or Develop a Model to Include the Effect of the Deviation Angle

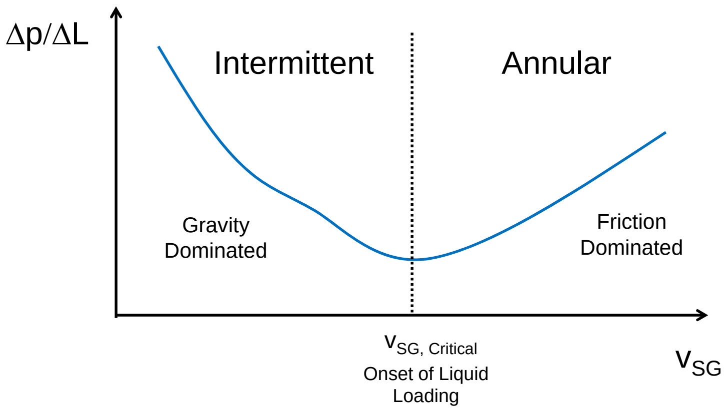
Introduction

- Gas Well Production Life



Introduction …

- Pressure Gradient versus Superficial Gas Velocity



Fluid Flow Projects

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Introduction …

- In Deviated Wells, Other Mechanisms are Important
  - Thicker Liquid Film at the Bottom of the Pipe Wall
  - Secondary Gas Flow in the Cross-Section

Fluid Flow Projects

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Literature Review

- Turner (1969) Model
  - Based on the Falling of Liquid Droplets
  - Applicable to Vertical Wells
- Belfroid *et al.* (2008) Model
  - Modified Turner Model for Deviated Wells
- Zabaras (1986) Experimental Study
  - Negative Wall Shear Stress for Fully Co-Current Flow
  - Wall Shear Stress Switch Signs After the Minimum Pressure Gradient

Literature Review …

- Westende (2008) Experimental Study
  - No Falling Liquid Droplets were Observed
- Yuan (2011) and Guner (2012) Experimental Studies
  - Onset of Liquid Loading Occurs at the Minimum Pressure Gradient
  - Liquid Film Reversal Flow Observed at the Onset Condition
  - Critical Gas Velocity Increases with Deviation Angle

Comments from Spring 2013 ABM

- Excluding 45° from the Test Matrix
  - Replaced with 60°

Experimental Study

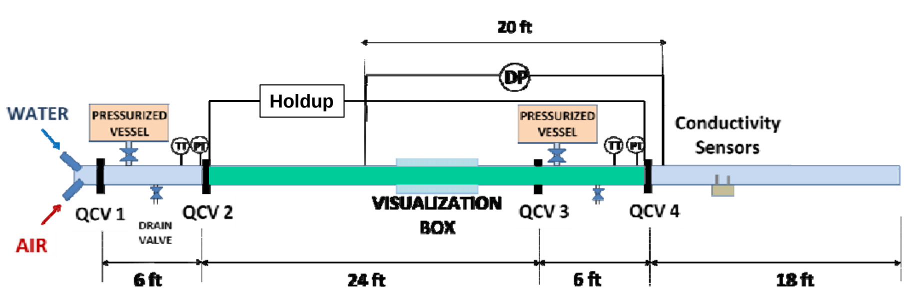
- Experimental Test Program
  - Test Matrix
  - Test Facility
  - Instrumentation
- Experimental Results
- Model Comparison and Development

Test Matrix

- Well Deviation Angle
  - 60°, 70°, 80°, 85° and 88°
- Superficial Liquid Velocity
  - 0.01, 0.02, 0.05 and 0.1 m/s
- Superficial Gas Velocity
  - 40 to 2 m/s
- Total of 288 Test Points

Test Facility

- Test Section Design
  - 3 in x 17.5 m



Instrumentation

- Measuring Instruments
  - Flow Meters with PID Controllers
    - Mass Flow Rates
  - Pressure and Temperature Transducers
    - Absolute Pressure and Temperature
  - Sealed Impulse Lines with Pressure Transducer
    - Pressure Gradient

Instrumentation …

- Measuring Instruments
  - Long Trap Section with Quick-Closing Valves
    - Holdup
  - Conductivity Sensors
    - Wave Characteristics

Instrumentation …

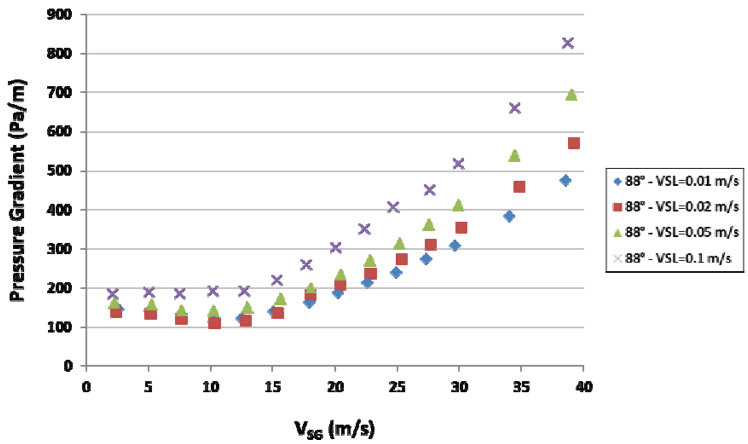
- Visual Observation
  - High-Speed Camera
    - Liquid Film Flow Direction
  - Outside Video Camera
    - Flow Behavior

Experimental Results

- Results for 88°, 80° and 70°
  - Pressure Gradient
  - Liquid Holdup
  - Structure Frequency
  - Flow Pattern

Experimental Results …

- 88° - Pressure Gradient vs. Superficial Gas Velocity



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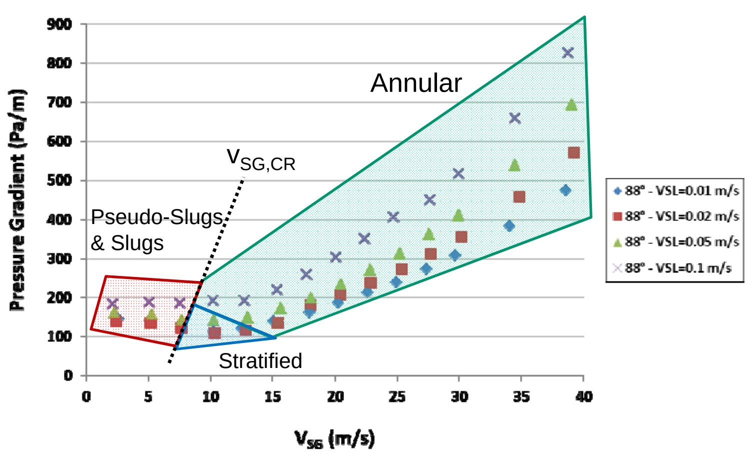
Experimental Results …

- 88° - Pressure Gradient vs. Superficial Gas Velocity



Fluid Flow Projects

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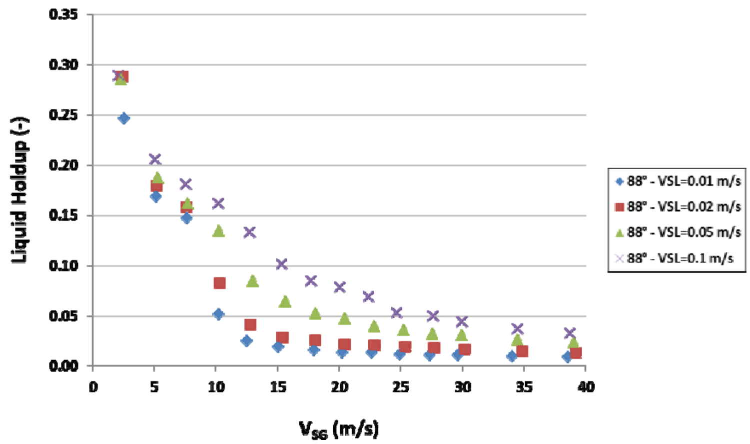
Experimental Results …

- 88° - Liquid Holdup vs. Superficial Gas Velocity



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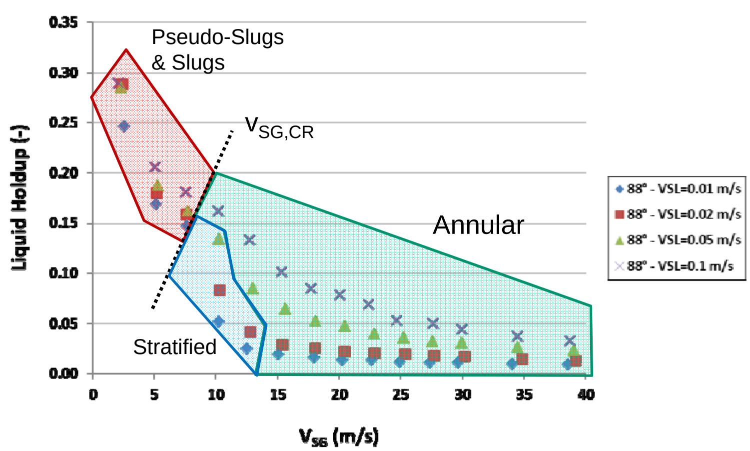
Experimental Results …

- 88° - Liquid Holdup vs. Superficial Gas Velocity



Fluid Flow Projects

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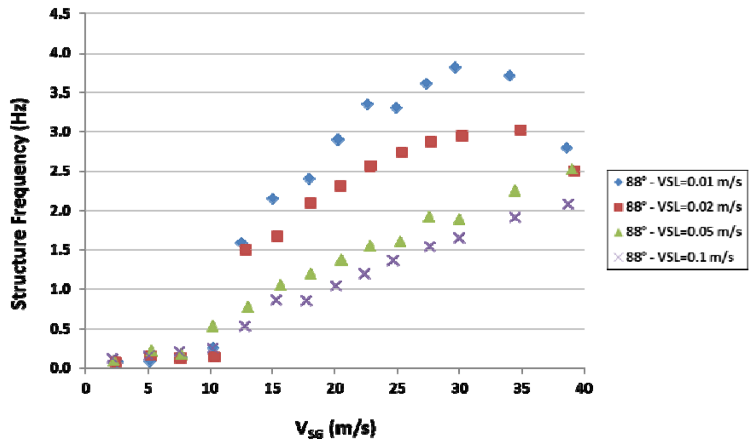
Experimental Results …

- 88° - Structure Frequency vs. Superficial Gas Velocity



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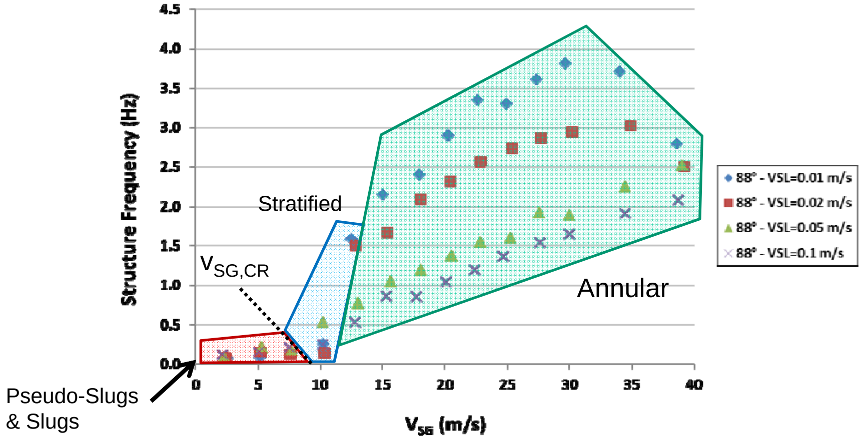
Experimental Results …

- 88° - Structure Frequency vs. Superficial Gas Velocity



Fluid Flow Projects

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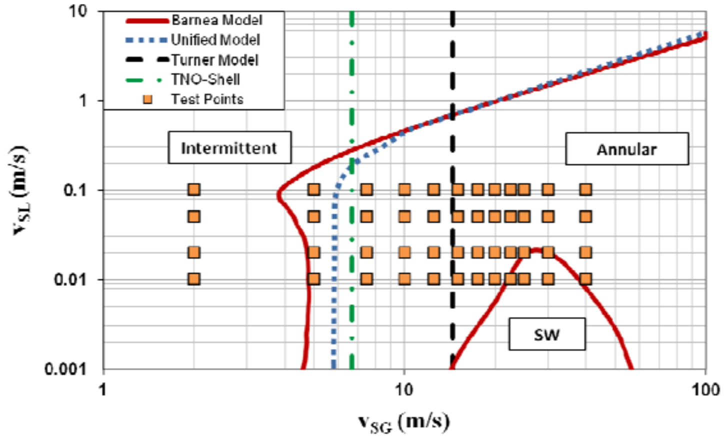
Experimental Results …

- 88° - Flow Pattern Map

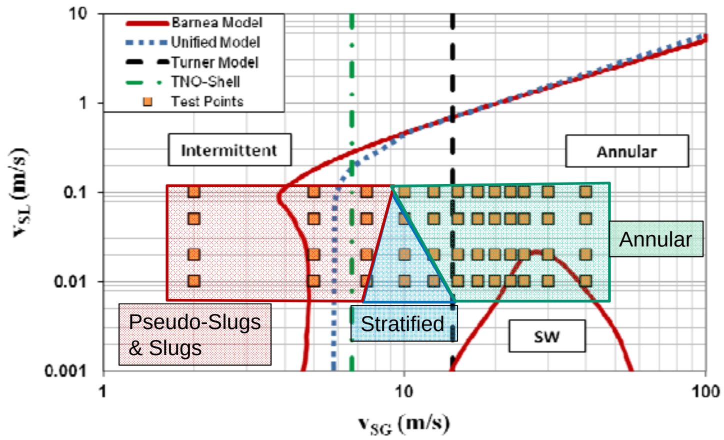


Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Experimental Results …

- 88° - Flow Pattern Map

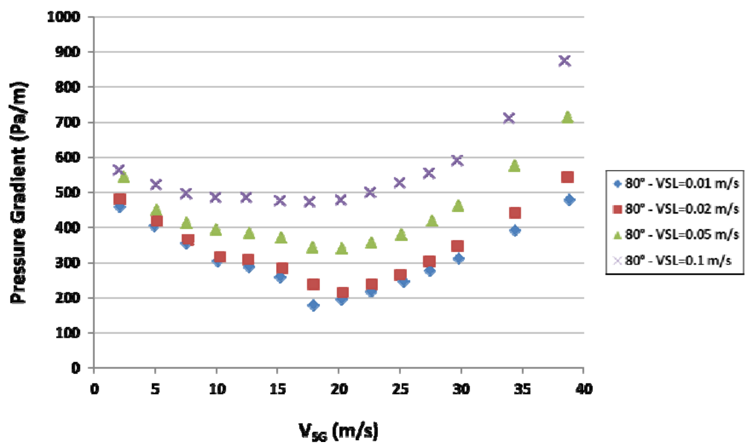


Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Experimental Results …

- 80° - Pressure Gradient vs. Superficial Gas Velocity

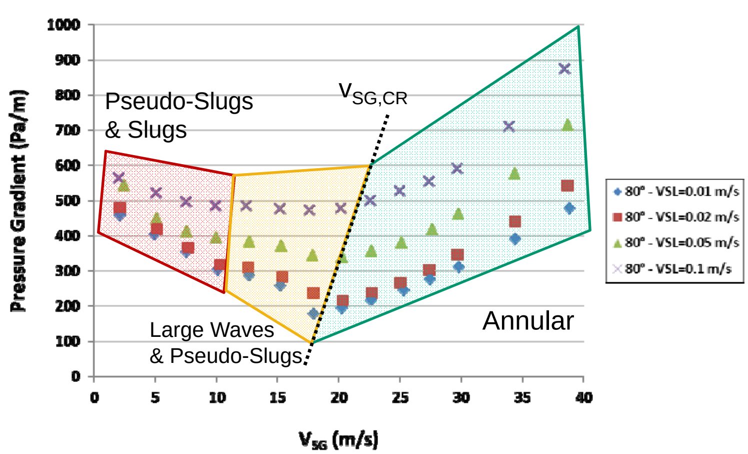


Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Experimental Results …

- 80° - Pressure Gradient vs. Superficial Gas Velocity

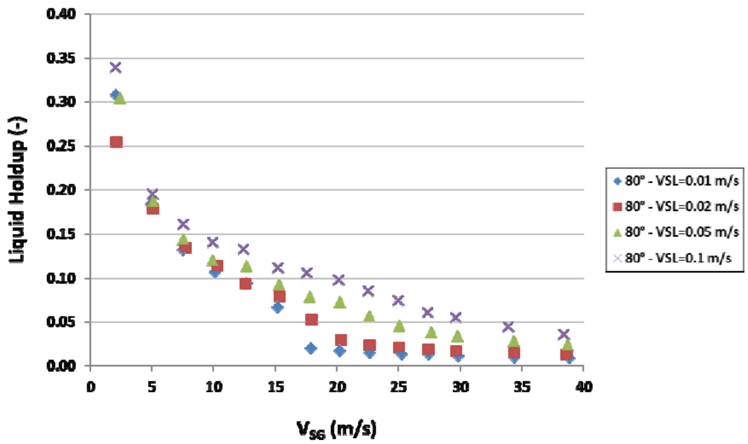


Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Experimental Results …

- 80° - Liquid Holdup vs. Superficial Gas Velocity



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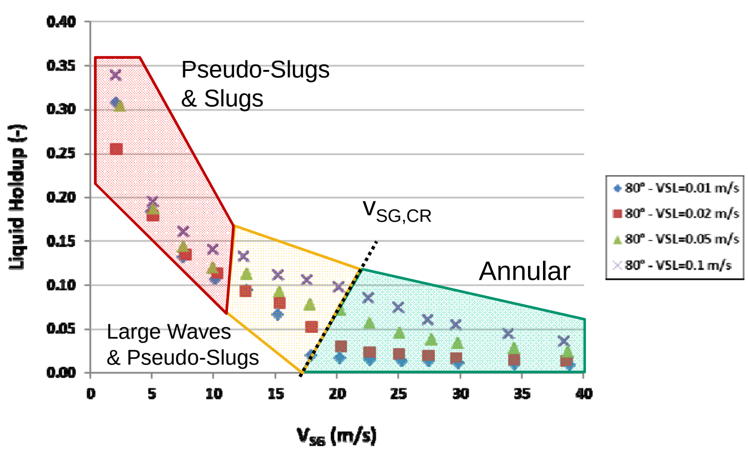
Experimental Results …

- 80° - Liquid Holdup vs. Superficial Gas Velocity



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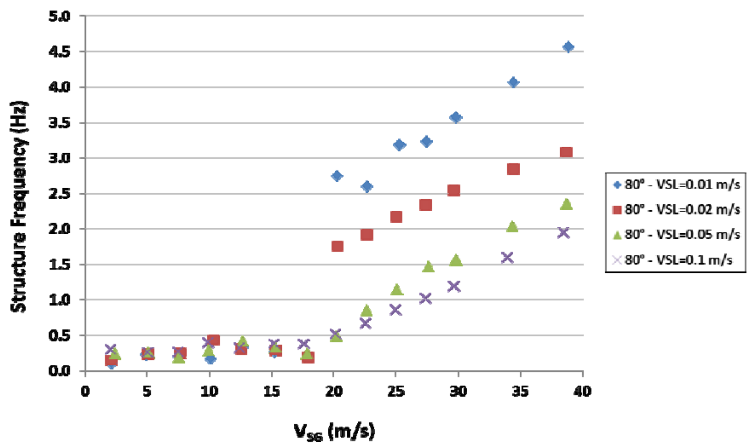
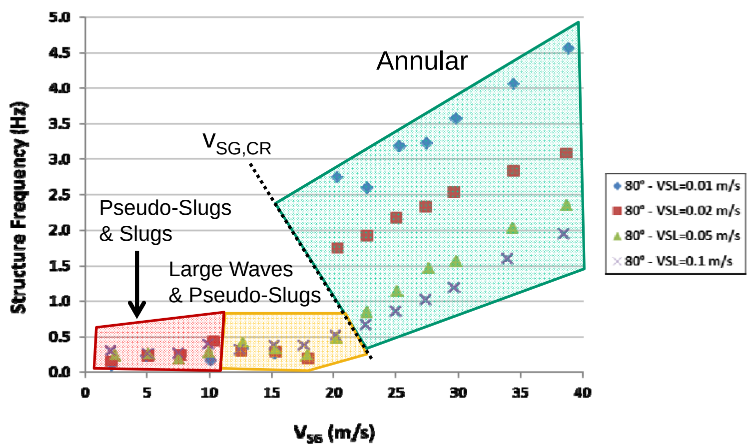
Experimental Results …

- 80° - Structure Frequency vs. Superficial Gas Velocity



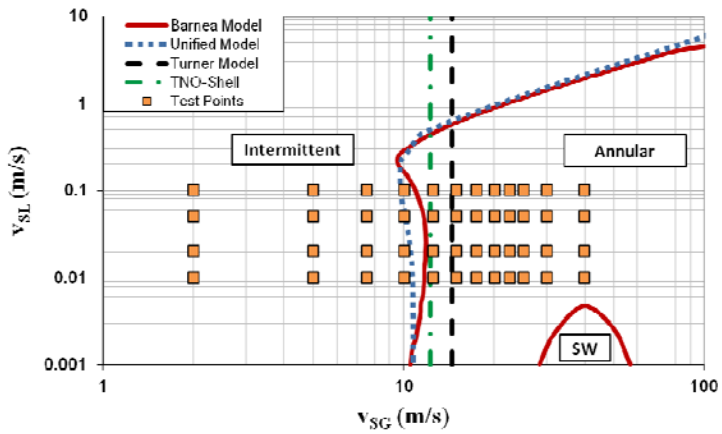
Experimental Results …

- 80° - Structure Frequency vs. Superficial Gas Velocity



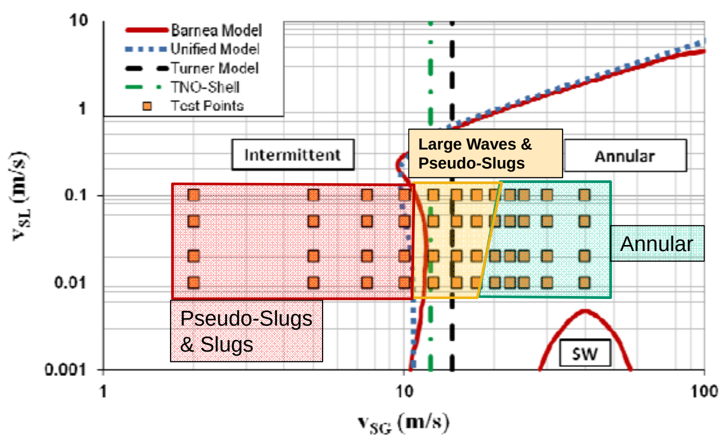
Experimental Results …

- 80° - Flow Pattern Map



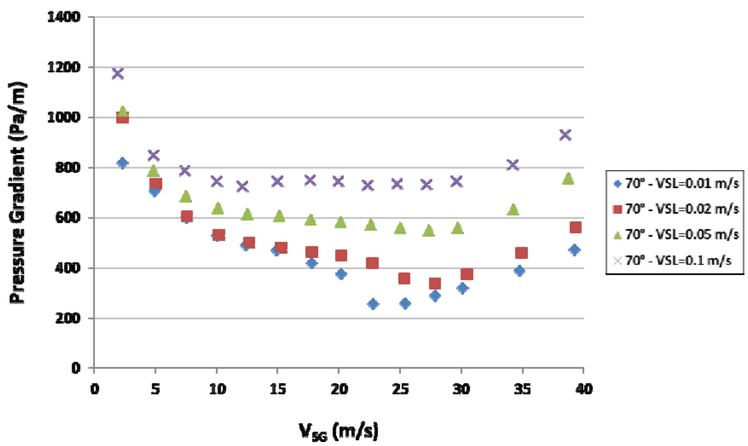
Experimental Results …

- 80° - Flow Pattern Map



Experimental Results …

- 70° - Pressure Gradient vs. Superficial Gas Velocity



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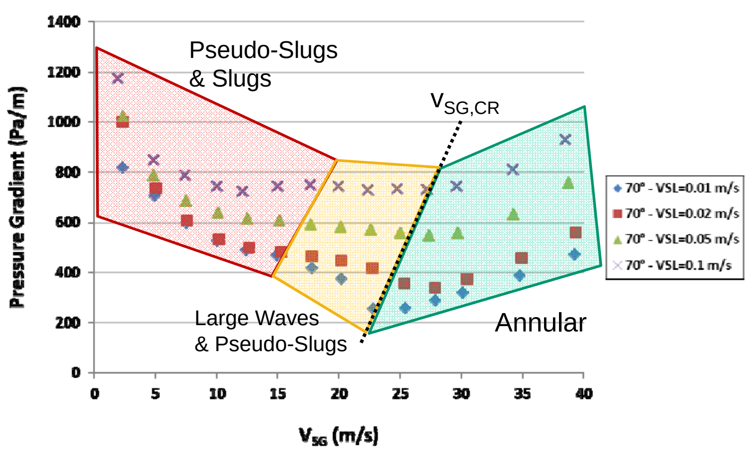
Experimental Results …

- 70° - Pressure Gradient vs. Superficial Gas Velocity



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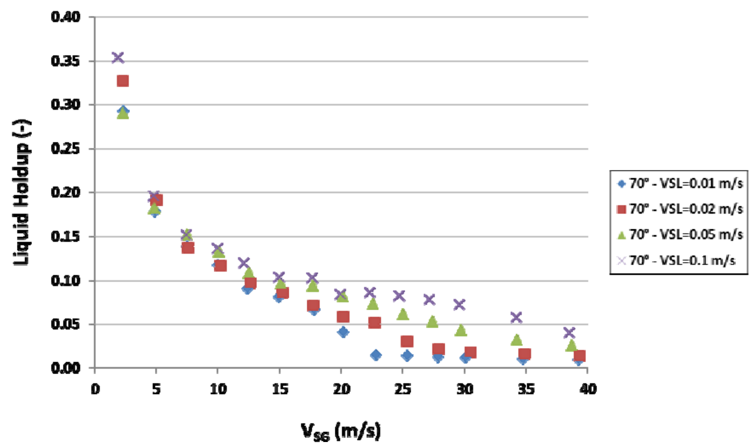
Experimental Results …

- 70° - Liquid Holdup vs. Superficial Gas Velocity



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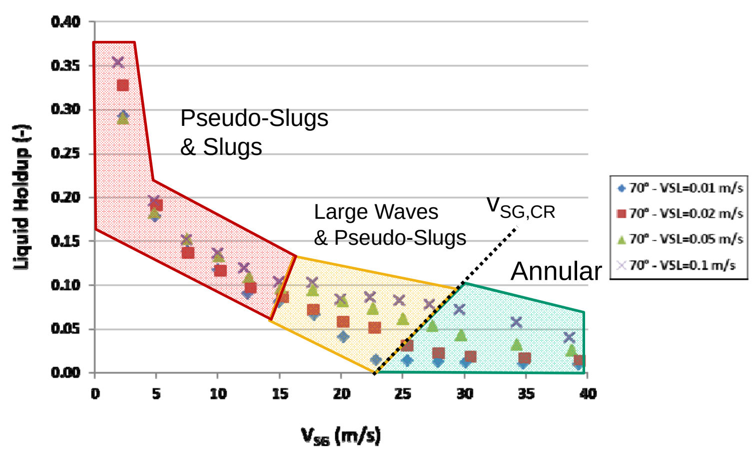
Experimental Results …

- 70° - Liquid Holdup vs. Superficial Gas Velocity



Fluid Flow Projects

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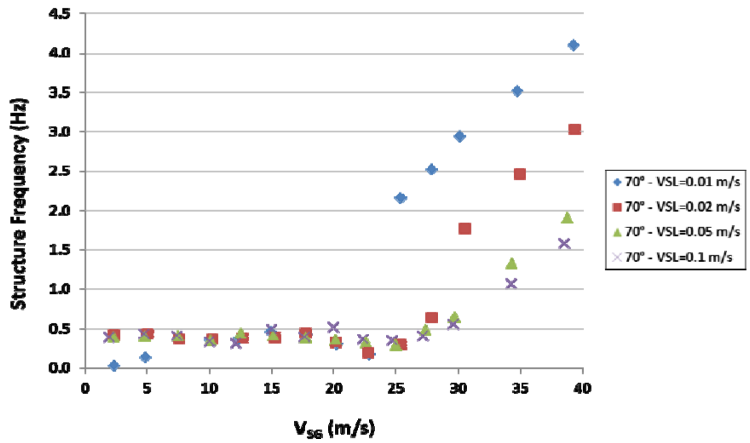
Experimental Results …

- 70° - Structure Frequency vs. Superficial Gas Velocity



Fluid Flow Projects

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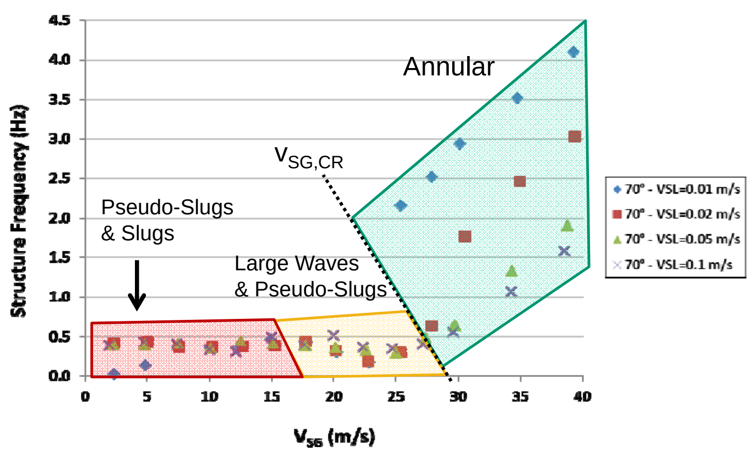
Experimental Results …

- 70° - Structure Frequency vs. Superficial Gas Velocity



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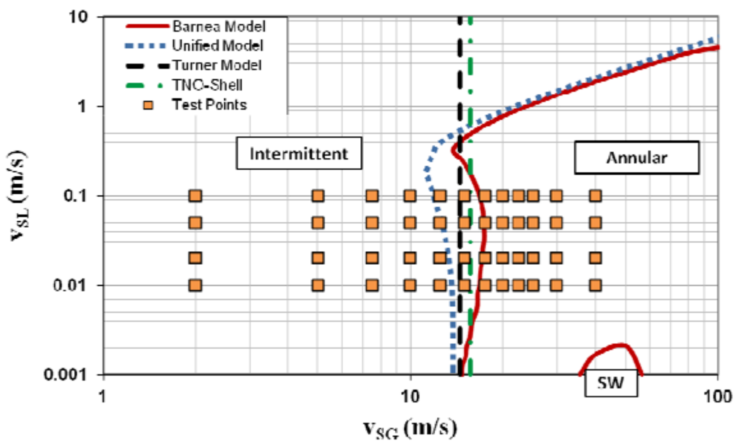
Experimental Results …

- 70° - Flow Pattern Map



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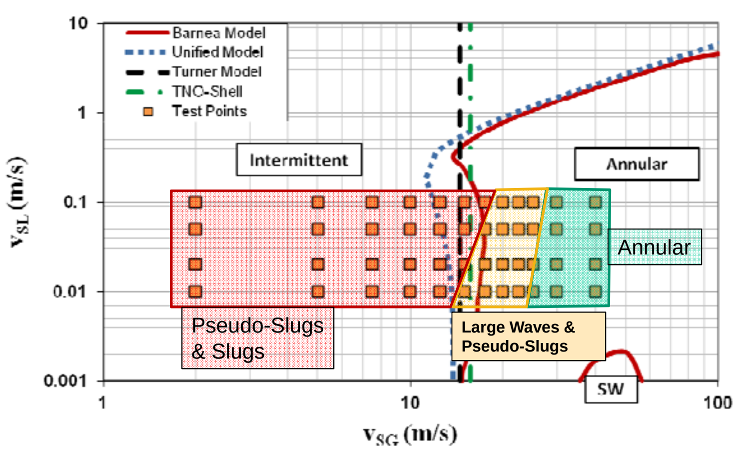
Experimental Results …

- 70° - Flow Pattern Map



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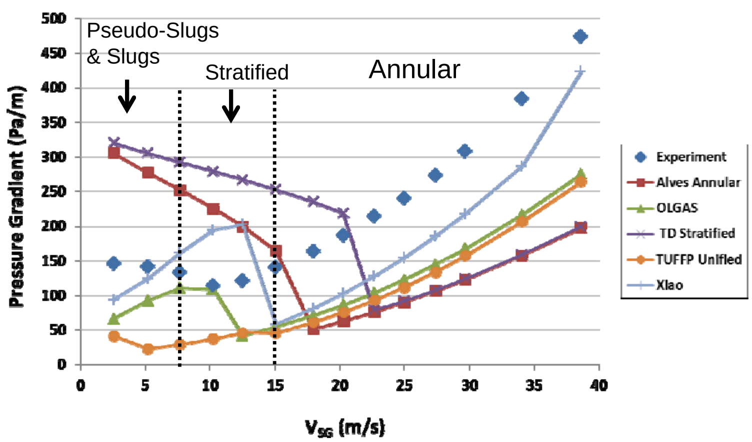
Model Comparison

- Experimental Results are Compared with the Following Models
  - Alves *et al.* Annular Model
  - OLGAS v7.2.3
  - Taitel and Dukler Stratified Model
  - TUFFP Unified Model (2012 v2)
  - Xiao Model

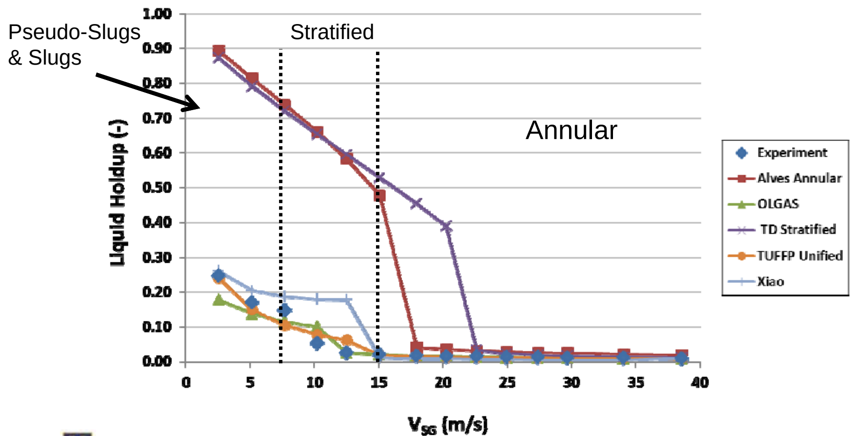
Model Comparison …

- Pressure Gradient – 88° - v_{SL} = 0.01 m/s (Alves Annular and TD Stratified: $f_i = f_G$)



Model Comparison …

- **Liquid Holdup – 88° - v_{SL} = 0.01 m/s (Alves Annular and TD Stratified: $f_i = f_G$)**



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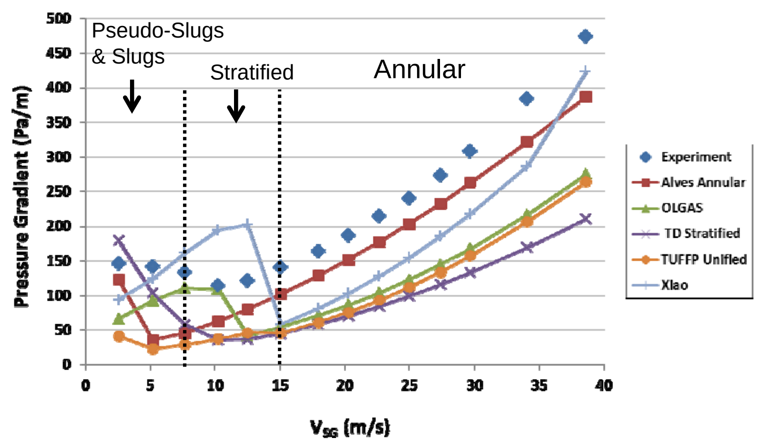
Model Comparison …

- **Pressure Gradient – 88° - v_{SL} = 0.01 m/s (Alves Annular and TD Stratified: f_i = Wallis)**



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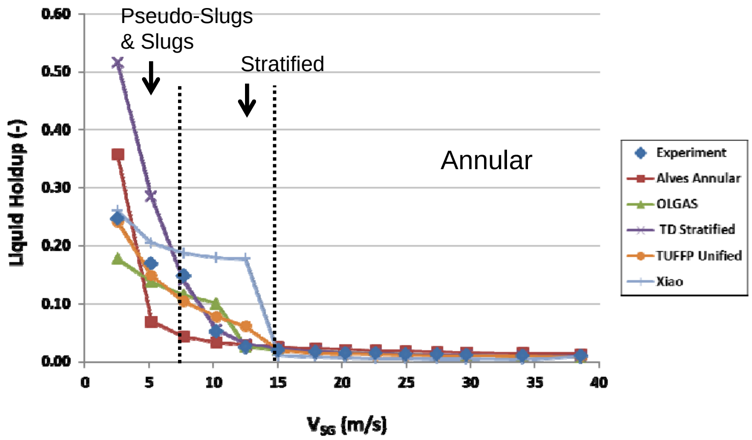
Model Comparison …

- **Liquid Holdup – 88° - v_{SL} = 0.01 m/s (Alves Annular and TD Stratified: f_i = Wallis)**



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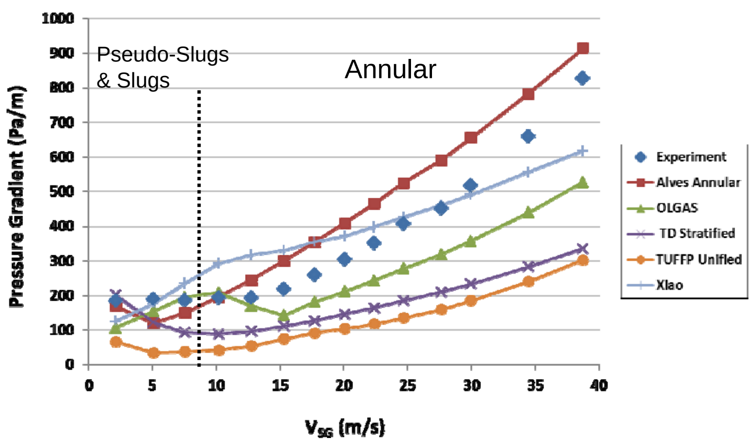
Model Comparison …

- **Pressure Gradient – 88° - v_{SL} = 0.1 m/s (Alves Annular and TD Stratified: f_i = Wallis)**



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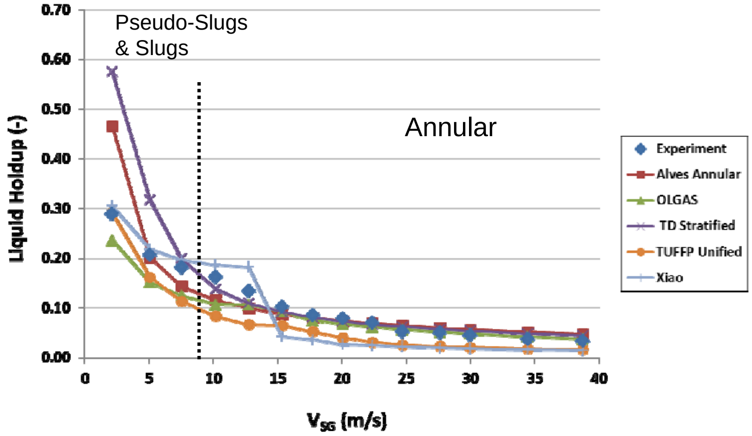
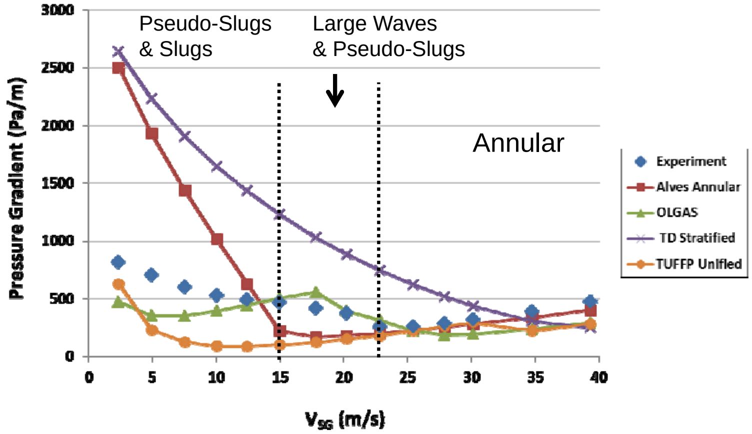
Model Comparison …

- **Liquid Holdup – 88° - v_{SL} = 0.1 m/s (Alves Annular and TD Stratified: f_i = Wallis)**



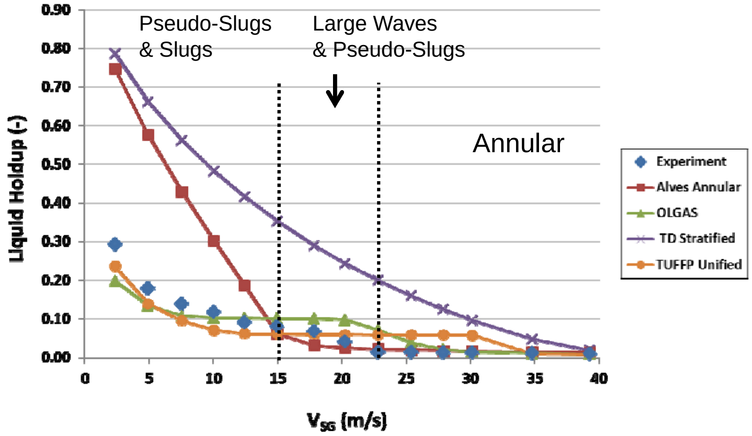
Model Comparison …

- **Pressure Gradient – 70° - v_{SL} = 0.01 m/s (Alves Annular and TD Stratified: f_i = Wallis)**



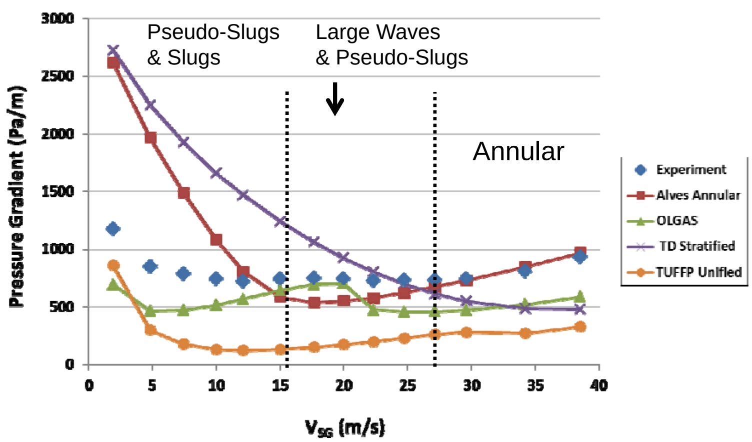
Model Comparison …

- **Liquid Holdup – 70° - v_{SL} = 0.01 m/s (Alves Annular and TD Stratified: f_i = Wallis)**



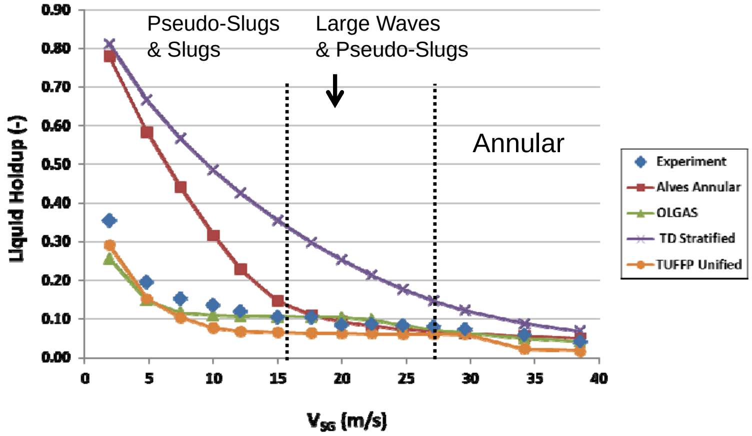
Model Comparison …

- **Pressure Gradient – 70° - v_{SL} = 0.1 m/s (Alves Annular and TD Stratified: f_i = Wallis)**



Model Comparison …

- Liquid Holdup – 70° - v_{SL} = 0.1 m/s (Alves Annular and TD Stratified: f_i = Wallis)



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Model Development

- Ongoing Task
- Predicting Critical Gas Velocity
- Predicting Pressure Gradient After the Onset of Liquid loading
- Predicting Liquid Holdup After the Onset of Liquid Loading

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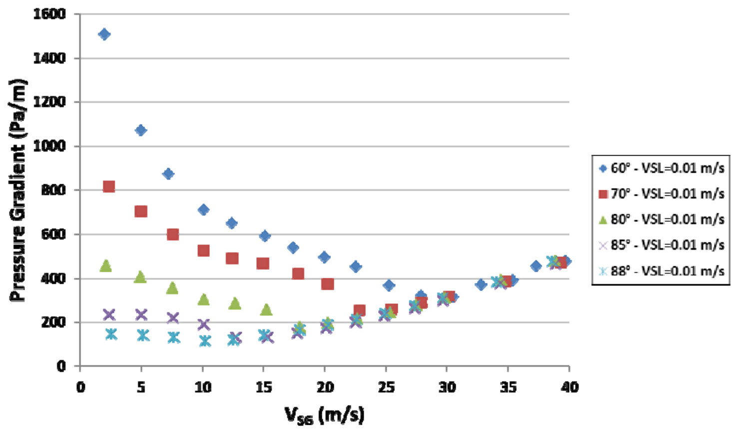
Model Development …

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



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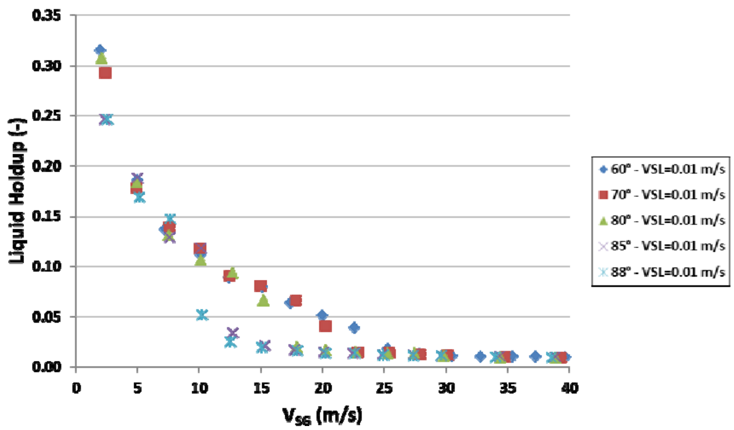
Model Development …

- Liquid Holdup – v_{SL} = 0.01 m/s



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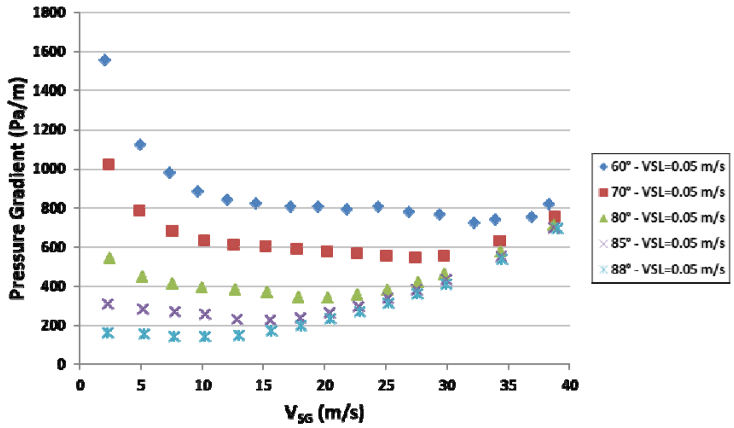
Model Development …

- Pressure Gradient – v_{SL} = 0.05 m/s



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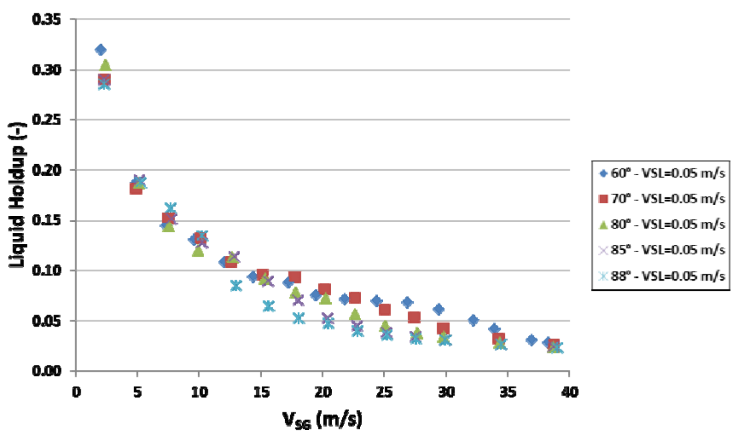
Model Development …

- Liquid Holdup – v_{SL} = 0.05 m/s



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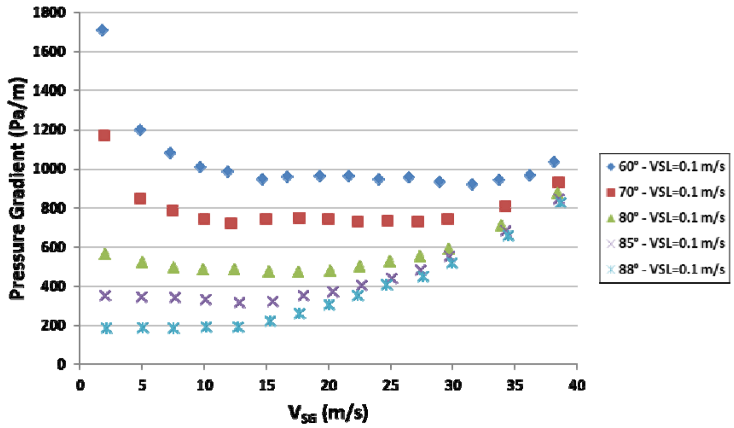
Model Development …

- Pressure Gradient – v_{SL} = 0.1 m/s



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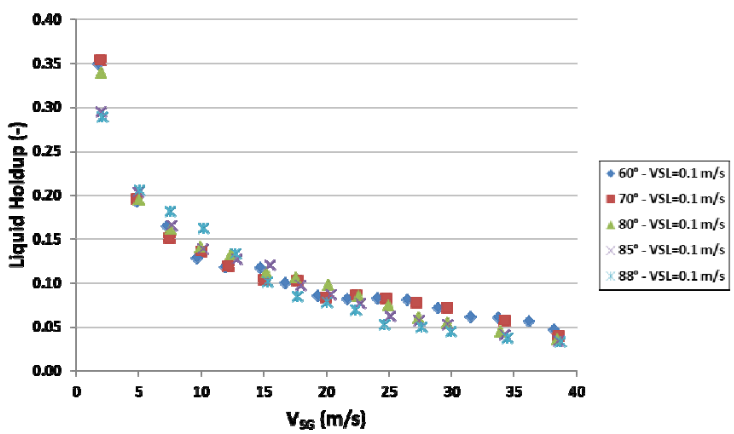
Model Development …

- Liquid Holdup – v_{SL} = 0.1 m/s



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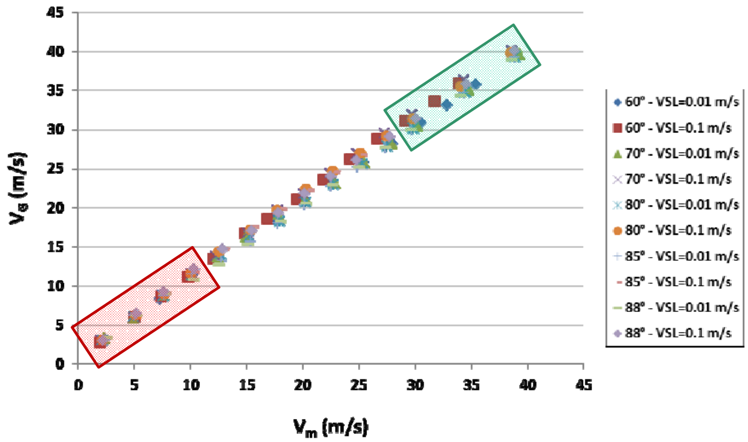
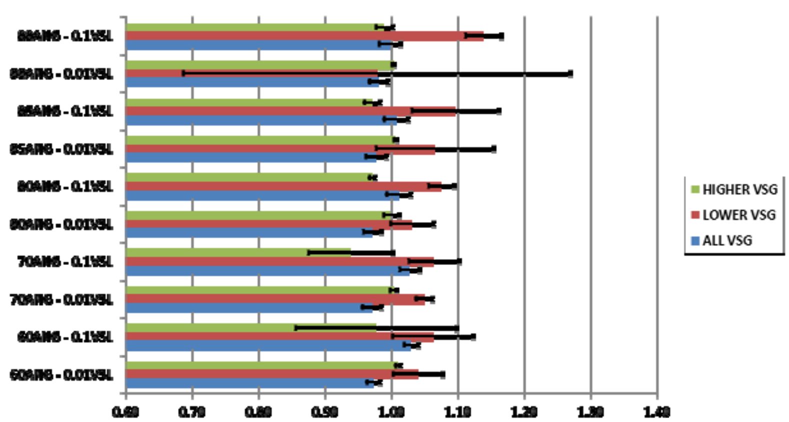
Model Development …

- Actual Gas Velocity vs. Mixture Velocity



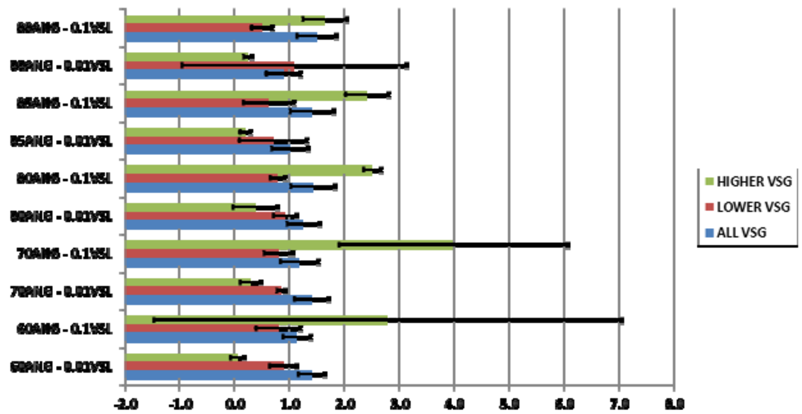
Model Development …

- Actual Gas Velocity vs. Mixture Velocity - Slope



Model Development …

- Actual Gas Velocity vs. Mixture Velocity - Intercept



Conclusions

- 5 Deviation Angles from 60° to 90°
- Critical Gas Velocity Decreases When Deviation Angles Increase
- At 70° and 60°, Large Waves with Local Back Flow of Liquid Film was Observed after the Onset of Liquid Loading

Conclusions ...

- Slugs are Observed When v_{SG} is Below 15 m/s
- Slugs are More Developed at Higher v_{SL}
- Slugs are Created When the Liquid Film Falls Back and Blocks the Inlet
- Frequency of Slugs is Low (0.5 Hz)

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Project Schedule

Literature Review	Completed
Experimental Testing	Completed
Data Analysis	Completed
Model Comparison	Completed
Model Development	October 2013
Final Report	November 2013

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Questions
&
Comments

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Liquid Loading In Deviated Pipes From 60° to 90°

Yasser Alsaadi

Project Completion Dates

Literature Review	Completed
Experimental Testing	Completed
Data Analysis	Completed
Model Comparison	Completed
Model Development	October 2013
Final Report	November 2013

Objective

The main objective of this study is to investigate the mechanism of liquid loading in highly deviated wells and pipes from 60° to 90°.

Introduction

Liquid loading happens in gas wells when the gas flow rate is not sufficient to lift the liquid to the surface. At this point, liquid starts to accumulate at the bottom of the well and creates a liquid column. This phenomenon is common in matured gas fields, and poses a serious production problem.

The onset of liquid loading is identified as the gas reaches a critical velocity at which the liquid falls back. To explain the mechanism behind it, Turner (1969) suggested that at the critical gas velocity the gravity on the liquid droplets balances the drag force of the gas and proposed a model accordingly. Several researchers attempted to improve Turner's (1969) model including Belford's (2008) modification to account for the deviation angle.

Another mechanism to explain the initiation of liquid loading was proposed later; it is based on the reversal flow of the liquid film. Zabaras (1986) observed that at liquid loading condition, the wall shear stress switched signs, indicating a change in the liquid film flow direction. In 2008, Westenende concluded that no falling droplets were observed in the transition to churn flow. In addition, Yuan (2011) and Guner (2012) observed partial reverse flow of the liquid film near the wall at the onset of liquid loading using a high-speed camera.

In deviated wells, other mechanisms affect liquid loading. The gravity force on the droplet decreases with deviation and a thicker liquid film exists at the bottom wall of the pipe. In addition, a secondary gas flow in the cross-section of the pipe is created and affects the film distribution around the pipe wall and the entrainment of droplets.

Activities Summary

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

Experimental Program

The experiment was conducted to investigate liquid loading at the following deviation angles: 60°, 70°, 80°, 85° and 88°. Four superficial liquid velocities were tested at each angle: 0.01, 0.02, 0.05 and 0.1 m/s. For each superficial liquid velocity, pressure gradient, liquid holdup and wave characteristics were measured at each superficial gas velocity ranging from 40 m/s to 2 m/s with an interval of 2.5 m/s. The flow behavior was observed with a high-speed camera and a video camera.

Experimental Facility

The 76.2-mm (3-in.) diameter multiphase flow facility of Tulsa University Fluid Flow Projects (TUFFP) was utilized for the experiment. The total length of the pipe is 17.5 m. The facility is capable of being inclined from horizontal to vertical. Air and water were utilized as test fluids.

The facility is equipped with state-of-the-art instrumentation. The air and water flow rates are measured and controlled by flow meters and PID controllers. The absolute pressure and temperature are measured with pressure and temperature transducers. The pressure gradient is measured with a 6-m sealed impulse line with pressure transducers. One long trap section equipped with quick-closing valves is used to measure liquid holdup. Two conductivity sensors are used for wave characterization. A high-speed camera is used to observe the flow direction of the liquid film. In addition, a video camera is used to observe flow behavior.

Experimental Results

Before the Onset of Liquid Loading

This region is bounded by the highest superficial gas velocity and the critical gas velocity where liquid loading is initiated. The flow regime observed is annular flow. At 88°, stratified flow is found near the critical gas velocity. At 70° and 60°, for the highest liquid flow rate (v_{SL}=0.1 m/s), large waves were observed.

The pressure drop dominated by friction decreases with the gas flow rate. For the lowest liquid flow rate, the effect of the deviation angle on the pressure gradient is insignificant. For higher liquid flow rates, the pressure gradient decreases with the deviation angle. At 88° and v_{SL}=0.01 m/s, the minimum pressure gradient is found before the critical gas velocity.

Liquid holdup increases as gas flow rate decreases. The wave frequency decreases with the escalation of liquid flow rates and decreasing gas rate.

The Onset of Liquid Loading

The onset of liquid loading is recorded when a back flow of liquid film is observed. This is usually observed at the minimum pressure gradient. However, at 88° and v_{SL} =0.01 m/s, it is found to be after the minimum pressure drop, even though the change in pressure is small.

The flow pattern at the onset is annular with large waves and pseudo-slugs. The liquid film flows backward and changes direction with the large waves and pseudo-slugs.

The effect of the deviation angle is substantial and critical gas velocity increases when decreasing the deviation angle. For v_{SL}=0.01 m/s, the critical gas velocity at 88° is around 7.5 m/s, and at 70°, it is at 22.5 m/s. In addition, the effect of liquid flow rates on the onset condition increases with the decreasing of the deviation angle.

After the Onset of Liquid Loading

This region is bounded by the critical gas velocity and the lowest superficial gas velocity. It expands with the decrease of the deviation angle. The general description of flow pattern is intermittent. At 88°, the flow regime is slug and pseudo-slug. At 70°, large waves and pseudo-slugs are observed. As gas flow rate decreases, fewer large waves and more pseudo-slugs are found. With further decrease in the gas flow rate, slugs are observed, and fewer pseudo-slugs occur. The sizes of slug bodies are inconsistent and unstable with an aerated part near the upper wall. Most slugs are initiated at the inlet as the liquid falls back and blocks the inlet. Low slug frequency is observed.

The pressure drop dominated by gravity increases as the gas flow rate decreases. The effect of deviation is significant as the gravity effect decreases when the deviation angle increases. At 88°, the drop in pressure is very small. At 70°, the pressure drop increases as the gas flow rate decreases. However, at this angle and v_{SL}=0.1 m/s, the drop in pressure is small in the region where large waves and pseudo-slugs are observed.

Liquid holdup increases as the gas flow rate decreases. In the slug and pseudo-slug region, the holdup is less affected by the deviation angle for the same liquid flow rate.

Model Comparisons

The pressure gradient and liquid holdup from the experiment were compared with several existing models.

For pressure drop prediction, in the annular region (before the onset of liquid loading) and at v_{SL}=0.01 m/s, the Alves *et al.* (1991) annular flow model with Wallis's interfacial friction model have good agreement with experimental results. After the onset of liquid loading, no existing model showed reasonable agreement with experimental data.

For liquid holdup, in general, the predictions of the models are in better agreement with the results than for pressure drop. The Alves *et al.* annular model, TUFFP's unified model and the OLGA v7.2.3 model have good holdup prediction for annular flow. After the onset, TUFFP's unified model and the OLGA model better predict of the holdup.

Model Development – October 2013

Model development will be based on the results from the experiments. Three variables of interest in the model development are critical gas velocity, pressure gradient and liquid holdup.

Final Report – November 2013

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

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Fluid Flow Projects

Onset of Liquid Accumulation in Oil and Gas Pipelines

Yilin Fan

Outline

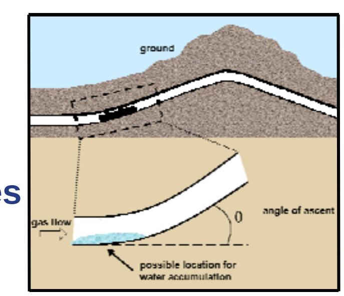
- Objectives
- Introduction
- Literature Review
- Experimental Program
- Near Future Tasks

Objectives

- Literature Study of Available Data for Onset of Liquid Accumulation and Velocity Profiles
- 2- and 3-phase Experimental Study in Available Flow Loop to Quantify Onset of Liquid Accumulation
- Comparison With the Available Models That can Predict the Onset of Liquid Accumulation
- Develop New Models If Necessary

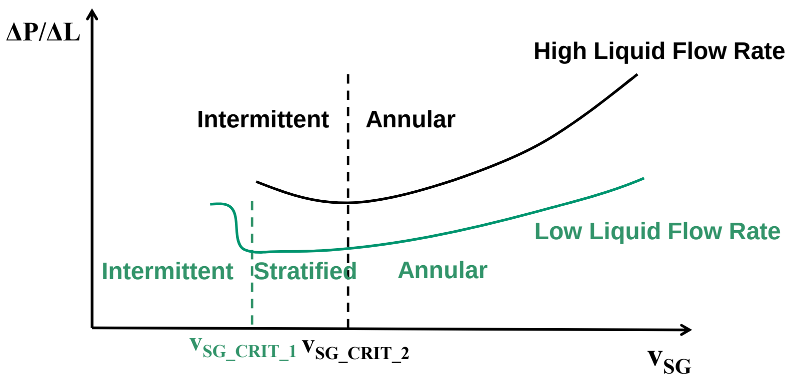
Introduction

- Liquid Accumulation in Inclined Pipes can Cause Corrosion and Terrain Slugging
- Accumulation Occurs Below Critical Gas Flow Rates
- Critical Gas Flow Rate Depends on:
  - Inclination Angle
  - Oil and Water Flow Rates
  - Liquid Properties



Introduction …

- Critical Gas Flow Rate



Fluid Flow Projects

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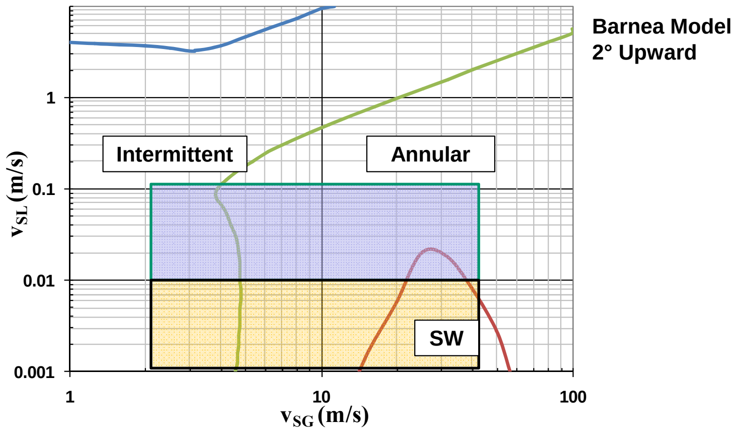
Introduction …

- Investigate Lower Liquid Flow Rate Region



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Introduction …

- **Waves Near Liquid Accumulation Region**
  - **Flow Simulators Do Not Consider This Type of Flow**
  - **Solid Transport**
  - **Pipeline Fatigue**

Slug

Waves

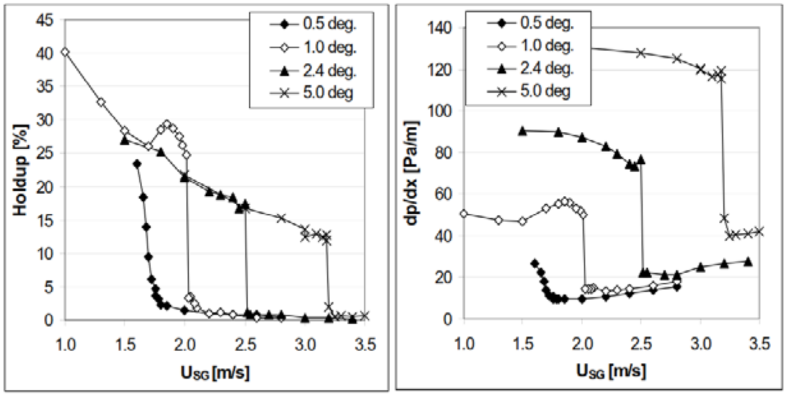
Literature Review

- **Langsholt and Holm (2007)**
  - **Slightly Upward Inclined Pipes**
  - **Liquid Holdup Increases Discontinuously with Decreasing Gas Flow Rate**

Loop Pressure (bara) /Gas Density (kg/m^3)	3.5 / 22.6	7.1 / 46.9
Water Cut (%)	0, 15, 40, 60, 85, 100	0
Pipe Inclinations	0.5°, 1.0°, 2.4°, 5° Upward	
Superficial Liquid Velocity (m/s)	0.001	
Pipe Diameter (m)	0.1	

Literature Review …

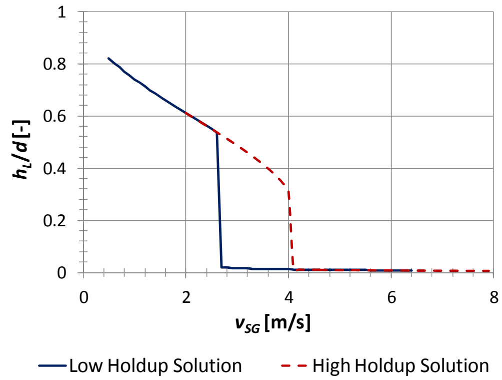
- Langsholt and Holm (2007) Results



($\rho_G = 22.6$ kg/m^3)

Literature Review …

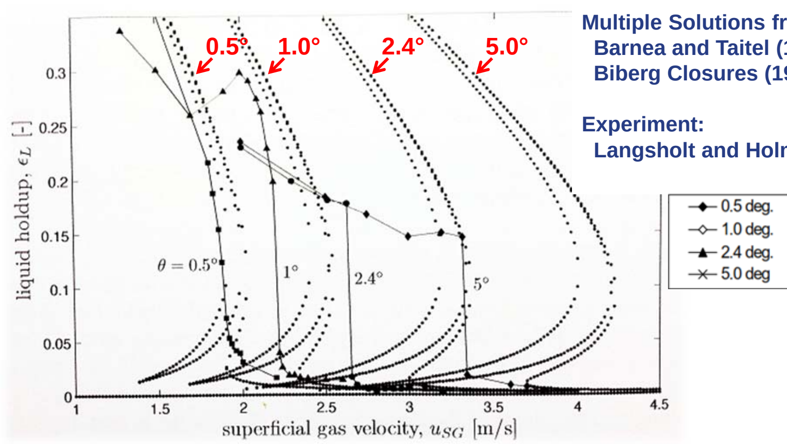
- Holdup Discontinuity Changes with Multiple Solution



Taitel & Dukler (1976)
$\rho_G = 22.6$ kg/m^3
$v_{SL} = 0.001$ m/s
$\theta = 2.4°$

Literature Review …

- Birvalski and Henkes (2012)



Multiple Solutions from Models:
Barnea and Taitel (1992)
Biberg Closures (1999)

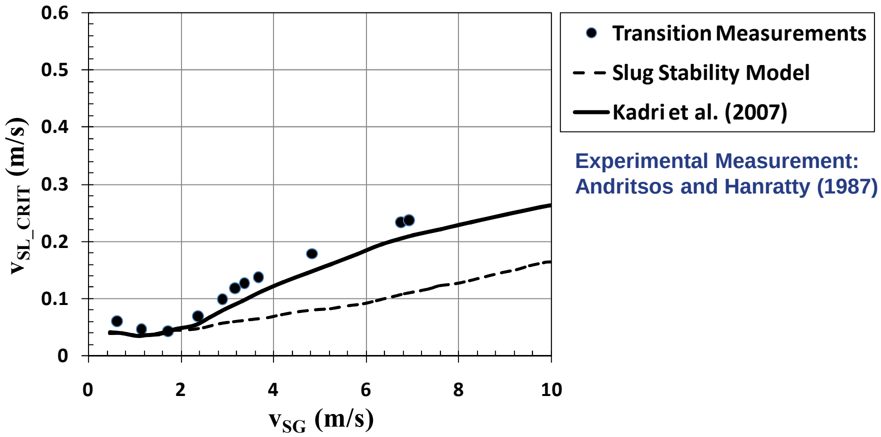
Experiment:
Langsholt and Holm (2007)

Literature Review …

- Kadri *et al.* Model (2007)
  - New Theoretical Model of Onset of Slug Flow
    - Critical v_{SL} to Form Slug Flow
    - Critical v_{SG} to Initiate Roll Waves
  - Mechanism
    - Development of Perturbed Interface
  - Horizontal and Slightly Inclined Tubes

Literature Review …

- Critical v_{SL} to Form Slug Flow (Kadri *et al.*)



Experimental Measurement:
Andritsos and Hanratty (1987)

Experimental Program

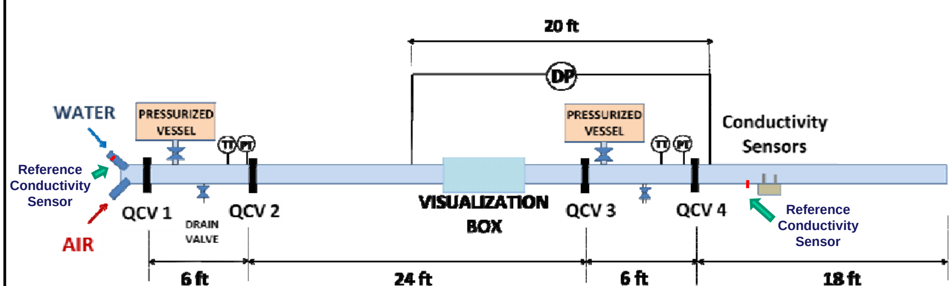
- 3-in and 6-in Facilities
- Air/Water and Air/Oil/Water
- Inclinations
  - 3-in Pipe: 1°, 2.5°, 5°, 10°, 15° and 20°
  - 6-in Pipe: 2°
- Water Cut
  - 0 to 100%
- Liquid Superficial Velocities
  - 0.001, 0.01, 0.05, 0.1 m/s

Measurements

- Pressure and Temperature
  - Pressure and Temperature Transducers
- Flow Rate
  - Flow Meters with PID Controllers
- Holdup
  - Quick Closing Valves
- Wave Characteristics
  - Conductivity Sensors
- Shear Stress / Velocity Profile (Upon Feasibility)

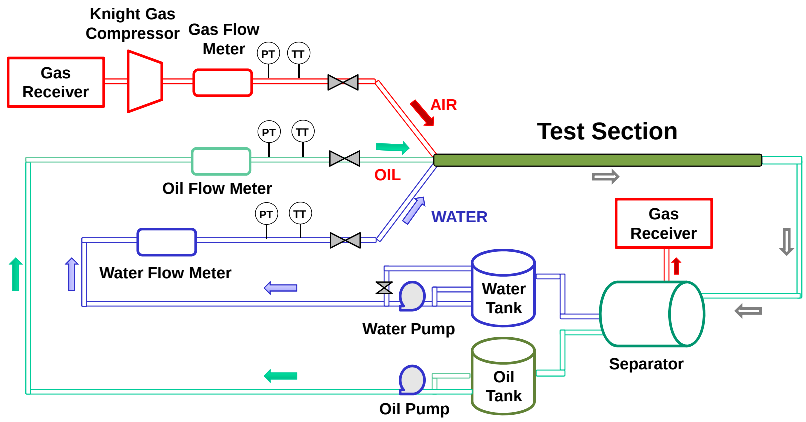
Experimental Facility

- 3-in Facility Test Section Design



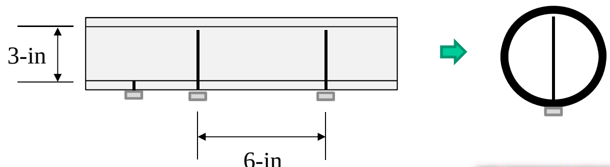
Experimental Facility …

3-in Facility Modification Design

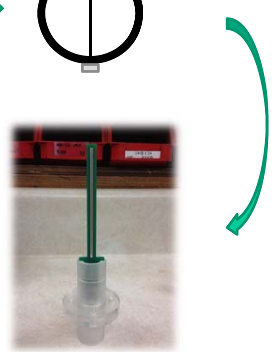


Wave Characteristics

Conductivity Sensors

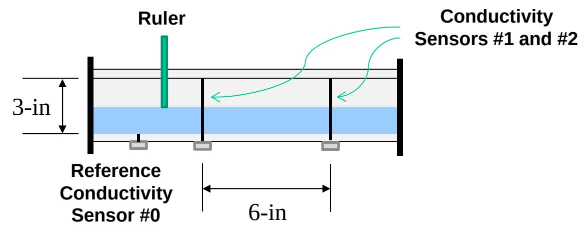


- Characteristics
  - Wave Length
  - Wave Celerity
  - Wave Frequency
  - Wave Amplitude



Wave Characteristics …

- Calibration Theory
  - Static Calibration



- Relationship between h_L and V/V_0

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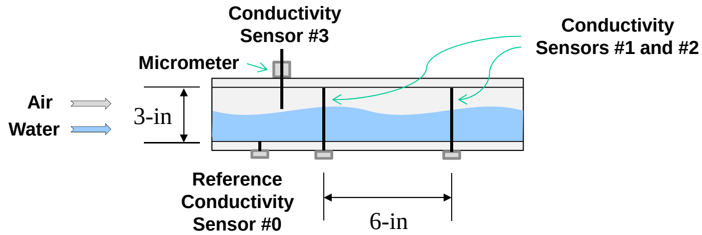
Wave Characteristics …

- Calibration Theory
  - Dynamic Calibration



- Mean Wave Height vs. V/V_0

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Near Future Tasks

- Literature Review on Liquid Accumulation
- Review of Velocity Profile and Wall Shear Stress Measurement Techniques
- Wave Characteristics Sensor Calibration
- Preliminary Air/Water Test
- 3-in Facility Modification

Schedule

Activity	2013					2014												2015												2016				
	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Literature Review	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
Facility Training		■										■	■																					
Facility Preparation		■	■		■	■	■						■	■	■	■	■																	
Experimental Study			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
- Test Matrix			■	■	■	■	■									■	■	■	■															
- Air/Water Test			■	■				■	■	■	■	■	■	■	■																			
- Air/Oil/Water Test																		■	■	■	■	■	■	■	■	■	■							
- Additional Test																■	■											■	■					
- Data Analysis		■	■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
Ph.D Proposal																								■										
Modeling Study								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
Dissertation Preparation																														■	■	■	■	
Defense																																		■

Question

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Onset of Liquid Accumulation in Oil and Gas Pipelines

Yilin Fan

Project Completion Dates

Literature Review	Ongoing
Facility Training and Preparation	Ongoing
Experimental Study - Air/Water	December 2014
PhD Proposal Defense	July 2015
Experimental Study - Air/Oil/Water	December 2015
Modeling Study	March 2016

Objectives

The main objectives of this project are as follows:

- Literature study of available data for onset of liquid accumulation and velocity profiles.
- Two- and three-phase flow experimental studies to quantify onset of liquid accumulation.
- Comparison with the available models that can predict the onset of liquid accumulation.
- Develop new models if necessary.

Introduction

Accumulation of liquid, oil and/or water at the bottom of an inclined pipe is known to be the source of many industrial problems, such as corrosion and terrain slugging. The accumulation of liquid takes place when the momentum transfer from the gas is too low to overcome the typical opposing forces of gravity of the liquid and to some extent friction, and is thus a function of several parameters. Accurate quantification of the required gas velocities to efficiently sweep the water out and prevent accumulation is of great importance, as is the accurate prediction of oil and water holdup. Parameters believed to impact the required gas velocity are the inclination angle, oil and water flow rates, gas densities (pressure) and liquid properties (density, viscosity, surface tension).

Currently, minimum gas velocity or critical angle requirements are being implemented with various success rates to prevent corrosion in multiphase pipelines. Those criteria are often found to be very conservative.

This project will conduct both experimental and modeling studies to better quantify the accumulated liquid volumes and the critical gas velocity/inclination angle, especially for lower liquid flow rate and large-diameter pipelines.

Literature Review

The most susceptible areas for internal corrosion in pipelines correspond to no-flow and water and/or solid accumulation regions. All the methods proposed for internal corrosion management require the use of flow simulators to predict the water accumulation regions (Mogohissi *et al*., 2002, Carimalo *et al*., 2008, Lagad *et al*., 2004, Moghissi *et al*., 2007 and Hauguel *et al*., 2008).

For wet gas systems, liquid holdup strongly depends on the inclination angle and gas velocity. For low flow rates, the liquid holdup can increase by two orders of magnitude, either with little change in the inclination angle or gas velocity. This region can only be predicted by mechanistic models, thus flow simulators equipped with mechanistic models are required for internal corrosion evaluation.

Langsholt and Holm (2007) presented an experimental study to determine the critical gas velocity where the holdup change occurs. Their experimental results have been used to evaluate and tune the critical gas velocity prediction by flow simulators. The tests were carried out in 0.1-m ID pipe diameter and four pipe inclinations between 0.5° and 5°. The experimental matrix consists of several water cuts (WC) covering the entire range form 0 – 100% WC, keeping the liquid superficial velocity at 0.001 m/s. Two different gas densities were considered, namely, 22.6 and 46.9 kg/m^3.

The critical gas flow rate where the holdup suddenly changes is related to the existence of multiple roots in the stratified flow model solution. Birvalski and Henkes (2012) investigated the occurrence of multiple solutions in stratified flow and compared with Langsholt and Holm's (2007) experimental data. They used Barnea and Taitel's (1992) steady-state and transient models with Biberg's (1999) closures (interfacial shear stress). The transient model was used to determine which solution physically exists. However, Biberg's model had to be modified case by case to get a good agreement.

Kadri *et al.* (2007) proposed a new theoretical model to determine the flow pattern transition in gas-liquid flow in horizontal and near horizontal pipes, and a prediction of critical superficial gas velocities at which roll waves start to initiate. The model was compared with some experimental datadata exhibiting good agreement. The initiation of roll waves and slugs is closely related to liquid accumulation, thus further modeling study is of great interest if the theory could be expanded to cases of higher inclination angles.

Experimental Program

The 3-in Gas/Oil/Water Flow Loop will be used for the main experimental study. Both Air/Water two-phase flow and Air/Oil/Water three-phase flow will be investigated. Different superficial liquid velocities (0.001, 0.01, 0.05 and 0.1 m/s) will be considered. In addition, six inclination angles (1°, 2.5°, 5°, 10°, 15° and 20°) in combination with five different water cuts (0 to 100%) will be included in the experimental matrix. The 6-in Gas/Oil/Water Low Pressure Flow Loop will be used to compare with existing experimental data and validate the final model.

Pressure drop, average liquid holdup and wave characteristics data will be acquired. Review of velocity profile and/or wall shear stress measurement devices are ongoing. Flow characteristics will be recorded using high-speed and high-definition cameras.

Preliminary modification design of the 3-in flow loop has been completed. The oil flow loop will be connected with the existing flow loop. Air, oil and water will be separated in a horizontal three-phase separator. New conductivity sensors will be used to measure wave characteristics: wave length, celerity, frequency and amplitude. Static and dynamic calibration will be conducted before the measurement. The conductivity section will consist of two sensors, six inches apart. A reference conductivity sensor installed in the water injection line or flush-mounted conductivity probe installed in the test section will be considered to account for the change of water conductivity with time.

Modeling Approach

Experimental data from 3-in straight pipe experiments will be used to calibrate the interfacial and wall shear stress in the two-fluid model. The existing models will be evaluated and a new model will be developed if necessary. The final model will be validated with 6-in straight pipe and Langsholt and Holm's (2007) experimental data.

Near Future Tasks

During the next period the literature review will continue as well as a review of all possible technique for velocity profile and wall shear stress measurements. The wave characteristics sensor will be statically and dynamically calibrated. Preliminary Air/Water two-phase experiments will be conducted. The 3-in Gas/Oil/Water facility will be modified.

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Langsholt, M., and Holm, H.: "Liquid Accumulation in Gas-Condensate Pipelines – An Experimental Study," International Conference on Multiphase Production Technology, 13, Edinburgh, 2007.

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Moghissi, O., Sun, W., Mendez, C., and Vera, J.: "Internal Corrosion Direct Assessment Methodology for Liquid Petroleum Pipelines," Paper No. 07169, Corrosion 2007, March 11 - 15, 2007, Nashville, Tennessee.

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Kadri, U., Mudde, R. F., and Oliemans, R. V. A.: "On the Prediction of the Transition from Stratified Flow to Roll Waves and Slug Flow in Horizontal Pipes," International Conference on Multiphase Production Technology, 13, 2007.

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Fluid Flow Projects

Unified Model Computer Code Update

Carlos F. Torres

Outline

- Status
- Unified Model – Computer Code Structure
- Pressure Gradient Module
- Closure Relations Module
- Testing Module
- Future Tasks
- Recommendations

Status

- Information Gathering — Completed
- New Code Layout — Completed
- Layout Test — Completed
- Closure Relations Module — Completed
- Flow Pattern Module — Completed
- Pressure Gradient Module — Ongoing
- Closure Relations Module Testing — Ongoing
- Flow Pattern Module Testing — Ongoing
- Pressure Gradient Module Testing — Ongoing
- Code Release — January 2014
- Closure Relation Recommendations — May 2014

Unified Model
Modified Code Structure

Main
Use Conts
Use PG
Use Testing

Module PG
Use Conts
Use FP, Single
Use Bubble, DisBub, Slug
Use Separate

Module Single
Use Conts, Numerics, Closures
Sub PG_single

Module Numerics

Module Conts

Module Testing

Module FP
Use Conts, Numerics, Closures
Sub FP_Unified
Sub FP_Barnea
Sub FP_Xiao
Sub FP_Ansary

Module Closures
Use Conts
Sub Friction
Sub Friction_AN
Sub Friction_ST
Sub Friction_SP
Sub Entrainment
Sub Wettability
Sub Slug_Len
Sub Slug_Drift
Sub Slug_Trans
Sub Slug_Holdup

Module Separate
Use Conts, Numerics, Closures
Sub PG_annular
Sub PG_separate
Sub PG_stratified

Module Slug
Use Conts, Numerics, Closures
Sub PG_slug

Module Bubble
Use Conts, Numerics, Closures
Sub PG_bubble

Module DisBub
Use Conts, Numerics, Closures
Sub PG_db

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Pressure Gradient Module

- Contains the Sub-Modules
  - Single
  - Separated
  - Slug
  - Bubble
  - Dispersed Bubble
- Each Sub-Module Contains a Specific Set of Closure Relationships
- Available List of Closure Relationships
- User Defined Closure Relationship

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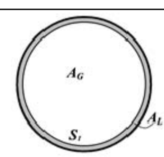
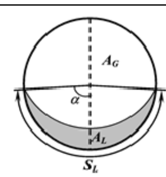
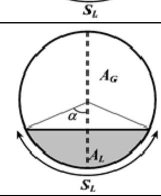
Separated Flow Sub-Module

Configuration		Characteristics
Annular		**Combined Momentum Equation:** Holdup **Closures Used**: Wall friction Interfacial friction Entrainment
Separated		**Combined Momentum Equation:** Holdup **Closures Used**: Wall frictions Interfacial friction Entrainment Wettability Interfacial length
Stratified		**Combined Momentum Equation:** Liquid level **Closures Used**: Wall frictions Interfacial friction Entrainment

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Slug Flow Sub-Module

- Under Development
- Uses Separated Flow Sub-Module
- Momentum Change Term On/Off to Allowed Different Slug Models
- Closures Used
  - Separated Region Inherited from Separated Flow Sub-Module
  - Slug Length & Frequency
  - Slug Drift Velocity
  - Slug Translational Velocity
  - Slug Body Holdup

Closure Relationships

Closure Code	*Wall Friction*	*Friction Stratified Flow*	*Friction Annular Flow*	*Friction Separated Flow*	*Entrainment Fraction*	*Wettability Angle*	*Slug Length & Frequency*	*Slug Drift Velocity*	*Slug Translational Velocity*	*Slug Body Holdup*
0	User defined	User defined	User defined	User defined	User defined	User defined	User defined	User defined	User defined	User defined
1	Blasius (1913)	Cohen & Hanratty (1968)	Wallis (1969)	Hart et al (1989)	Wallis (1969)	Hart et al (1989)	Taitel et al (1981)	Zhang et al (2003)	Fabre (1994)	Gregory et al (1978)
2	Hall (1957)	Andritsos & Hanratty (1987)	Wallis modified (1969)	Kowalski (1985)	Paleev & Filippovich (1966)	Grolman & Fortuin (1997)	Barnea & Brauner (1985)	Weber et al (1986)	Gokcal (2008)	Malnes (1982)
3	Churchill (1977)	Baker et al (1988)	Whalley & Hewitt (1978)	Taitel & Dukler (1976)	Oliemans et al (1986)	Fan (2005)	Gokcal et al (2010)	Moreiras et al (2013)		Ferschneider (1983)
4	Swamee & Jain (1976)	Bendiksen et al (1984)	Henstock & Hanratty (1976)	Vlachos et al (1997)	Zhang et al (2003)	Zhang & Sarica (2011)	Al-Safran et al (2013)	Jeyachandra et al (2012)		Andreussi & Bendiksen (1989)
5	Zigrang & Sylvester (1982)	Cheremisinoff & Davis (1979)	Oliemans et al (1986)	Wallis (1969)	Ishii & Mishima (1989)			Gokcal et al (2009)		Marcano (1996)
6	Haaland (1983)	Hart Et al (1989)	Asali et al (1985)	Wallis modified (1969)	Pan & Hanratty (2002 a & b)					Gomez et al (2000)
7	Colebrook (1939)	Kim Et al (1985)	Fore et al (2000)	Whalley & Hewitt (1978)	Sawant et al (2008)					Abdul-Majeed (2000)
8		Kowalski (1985)	Hamersma & Hart (1987)	Oliemans et al (1986)	Sawant et al (2009)					Barnea & Brauner (1985)
9		Andreussi & Persen (1987)	Fukano & Furukawa (1998)	Fore et al (2000)	Ousaka et al (1996)					Al-Safran (2009)
10		Taitel & Dukler (1976)	Dallman et al (1979)	Ambrosini et al (1991)	Al-Sarkhi et al (2012)					Zhang et al (2003)
11		Vlachos et al (1997)	Ambrosini et al (1991)	Hamersma & Hart (1987)						Kora et al (2012)
12			Govan et al (1991)	Chen et al (1997)						Al-Safran et al (2013)

Future Tasks

- Complete Missing Sub-Modules
- Testing
  - Closure Relationship Module
  - Flow Pattern Module with FFPDB
  - Pressure Gradient Module with FFPDB
- Data Clustering & Closure Relationship Recommendations

Recommendations

- Seamless Transition from Stratified to Annular
- Unified Closure Relationships Development

Comments and Suggestions

? ? ?

Unified Model Computer Code - Update

Carlos F. Torres

Project Completion Dates

Information Gathering	Completed
New Code Layout	Completed
Layout Test	Completed
Closure Relations Module	Completed
Flow Pattern Module	Completed
Pressure Gradient Module	Ongoing
Closure Relations Module Testing	Ongoing
Flow Pattern Module Testing	Ongoing
Pressure Gradient Module Testing	Ongoing
Code Release	January 2014
Closure Relation Recommendations Based on Data Clustering (Preliminary Results)	May 2014

Objective

The objective of this project is to develop and implement a new coding structure for the Unified Model.

Introduction

Several improvements in the Unified Model Computer Code are underway to develop a more flexible and robust steady-state two-phase flow calculation tool, and also to allow easy incorporation and testing of new closure relationships to extend/improve its prediction capabilities. Additionally, a new approach to solve the Unified Model was proposed to increase the computation efficiency and simplify the understanding of the Unified Model for Gas-Liquid.

Unified Model – Modules Update

The Unified Model Computer Code modular structure is shown in Fig. 1.

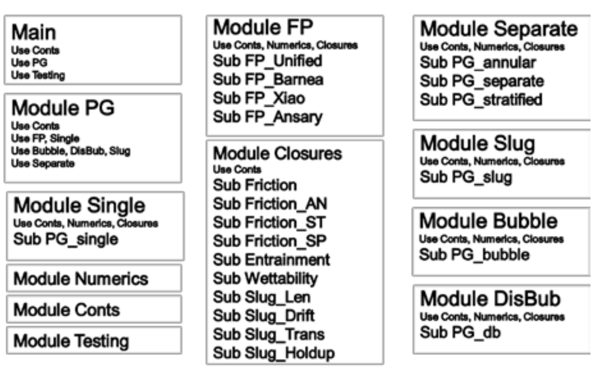


Figure 1. Modular Structure of the Unified Model Computer Code

As can be seen, the modular structure has been modified to include the testing module and to show the encapsulation of all closure relationships in one single module.

The development and individual testing of each module is a fundamental factor for the overall performance and robustness of the code. Currently, the coding process for several modules has been finished. The individual testing protocol has been developed for pressure gradient and closure relation modules.

Pressure Gradient Module

The pressure gradient module contains the single, separated, slug, bubble and dispersed bubble sub-modules. Each of these sub-modules contains a specific set of closure relationships. These specific closure relationships for each variable can be chosen by the user from the available list. Also, expert users can define their own closure for a specific variable.

The separated flow sub-module can solve three different interface configurations: annular, separated and stratified (see Table 1).

The slug flow sub-module is under development. It uses the separated flow sub-module to solve the separated region in the slug unit and it can turn the momentum change term on or off to facilitate the use of different slug flow models. Table 2 shows available closure relations for all the modules and sub-modules.

Testing Module

The testing module allows the comparison of the individual models, namely, pressure gradient for each flow pattern, flow pattern prediction and individual closure relationships predictions, with the experimental data given in the Fluid Flow Projects Database (FFPDB).

The testing module will be expanded in the future for the selection of the proper set of closure relationships for each flow pattern.

Table 1. Two-Fluid Model Configurations

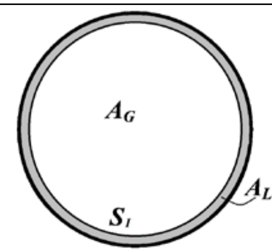
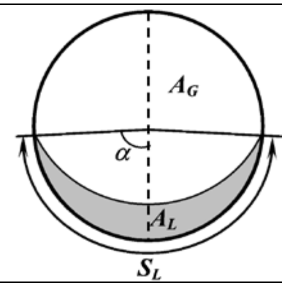
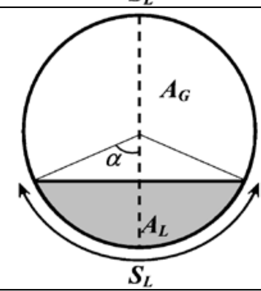
Configuration		Characteristics
Annular		**Combined Momentum Equation:** Holdup. **Closures Used**: Wall friction Interfacial friction Entrainment
Separated		**Combined Momentum Equation:** Holdup. **Closures Used**: Wall frictions Interfacial friction Entrainment Wettability Interfacial length
Stratified		**Combined Momentum Equation:** Liquid level. **Closures Used**: Wall frictions Interfacial friction Entrainment

Table 2. Closure Relationships Code Table

Closure Code	Wall Friction	Friction Stratified Flow	Friction Annular Flow	Friction Separated Flow	Entrainment Fraction	Wettability Angle	Slug Length & Frequency	Slug Drift Velocity	Slug Translational Velocity	Slug Body Holdup
0	User defined	User defined	User defined	User defined	User defined	User defined	User defined	User defined	User defined	User defined
1	Blasius (1913)	Cohen & Hanratty (1968)	Wallis (1969)	Hart et al (1989)	Wallis (1969)	Hart et al (1989)	Taitel et al (1981)	Zhang et al (2003)	Fabre (1994)	Gregory et al (1978)
2	Hall (1957)	Andritsos & Hanratty (1987)	Wallis modified (1969)	Kowalski (1985)	Paleev & Filippovich (1966)	Grolman & Fortuin (1997)	Barnea & Brauner (1985)	Weber et al (1986)	Gokcal (2008)	Malnes (1982)
3	Churchill (1977)	Baker et al (1988)	Whalley & Hewitt (1978)	Taitel & Dukler (1976)	Oliemans et al (1986)	Fan (2005)	Gokcal et al (2010)	Moreiras et al (2013)		Ferschneider (1983)
4	Swamee & Jain (1976)	Bendiksen et al (1984)	Henstock & Hanratty (1976)	Vlachos et al (1997)	Zhang et al (2003)	Zhang & Sarica (2011)	Al-Safran et al (2013)	Jeyachandra et al (2012)		Andreussi & Bendiksen (1989)
5	Zigrang & Sylvester (1982)	Cheremisinoff & Davis (1979)	Oliemans et al (1986)	Wallis (1969)	Ishii & Mishima (1989)			Gokcal et al (2009)		Marcano (1996)
6	Haaland (1983)	Hart Et al (1989)	Asali et al (1985)	Wallis modified (1969)	Pan & Hanratty (2002 a & b)					Gomez et al (2000)
7	Colebrook (1939)	Kim Et al (1985)	Fore et al (2000)	Whalley & Hewitt (1978)	Sawant et al (2008)					Abdul-Majeed (2000)
8		Kowalski (1985)	Hamersma & Hart (1987)	Oliemans et al (1986)	Sawant et al (2009)					Barnea & Brauner (1985)
9		Andreussi & Persen (1987)	Fukano & Furukawa (1998)	Fore et al (2000)	Ousaka et al (1996)					Al-Safran (2009)
10		Taitel & Dukler (1976)	Dallman et al (1979)	Ambrosini et al (1991)	Al-Sarkhi et al (2012)					Zhang et al (2003)
11		Vlachos et al (1997)	Ambrosini et al (1991)	Hamersma & Hart (1987)						Kora et al (2012)
12			Govan et al (1991)	Chen et al (1997)						Al-Safran et al (2013)

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Fluid Flow Projects

TUFFP Experimental Database (FFPDB)

Jinho Choi

Advisory Board Meeting, September 25, 2013

Outline

- Objective
- Purpose
- FFPDB Version 1.1
  - List of Data Sets
  - Variables
  - User Interface
  - Data Import and Export Demonstration
- Future Work

Objective

- Development of Multiphase Flow Database
  - Two-Phase : Gas-Liquid, Liquid-Liquid
    Three-Phase : Gas-Liquid-Liquid
  - Steady-State Flow Data
  - Transient Flow Data

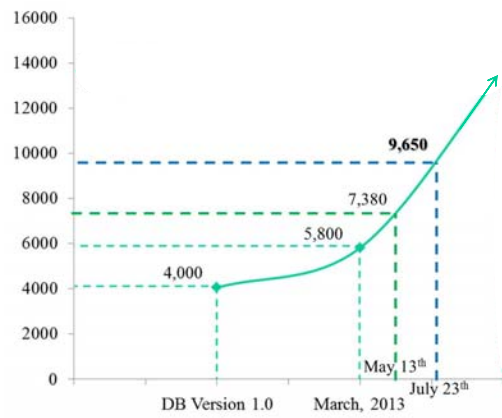
Purpose

- Validate Developed Models for Multiphase Pipe Flow
- Export Data into a Required Format for Testing
- Import New and Undefined Data Sets

➔ *Usability, Applicability, Extensibility*

FFPDB Version 1.1

Database Progress



- Data Sets That Will be Included Soon

Author	Year	Phases	# of Data
Sylvester et al.	1977	Gas-Liquid	?
Akpan	1980	Gas-Liquid	277
Fernandez	1982	Gas-Liquid	35
Ihara	1991	Gas-Liquid	?
Alves	1991	Gas-Liquid	546
Gonzalez	1993	Gas-Liquid	24
Wang	2003	Gas-Liquid	87
TUFFP Wellbore Databank		Gas-Liquid	2052
Arirachakaran	1983	Oil-Water	?
Martinez	1985	Oil-Water	?
Trallero	1995	Oil-Water	?

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

FFPDB Version 1.1

Data Sets Requiring More Process for Incorporating

Author	Year	Phases	# of Data	Note
Palmer	1975	Gas-Liquid	29	hilly terrain
Payne	1975	Gas-Liquid	70	hilly terrain
Scoggins, Jr.	1977	Gas-Liquid	6	transient
Dutta-Roy	1984	Gas-Liquid	16	transient
Zheng	1991	Gas-Liquid	115	hilly terrain
Minami	1991	Gas-Liquid	60	transient, Pigging
Vigneron	1995	Gas-Liquid	18	transient
Al-Safran	1999	Gas-Liquid	20	hilly terrain
Al-Safran	2003	Gas-Liquid	105	hilly terrain
Gokcal	2010	Gas-Oil-Water	100	hilly terrain
Schmidt	1976	Gas-Liquid	81	Pipeline-Riser
Juprasert	1976	Gas-Liquid	146	Pipeline-Riser
Schmidt	1977	Gas-Liquid	286	Pipeline-Riser
Tengesdal	2002	Gas-Liquid	51	Pipeline-Riser
Beltran	2005	Gas-Oil-Water	?	Pipeline-Riser
Caetano	1984	Gas-Liquid	344	Casing-tubing
Caetano	1985	Gas-Liquid	734	Casing-tubing
Barua	1982	Gas-Liquid	45	pigging

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

FFPDB Version 1.1 …

- **Steady-State Multiphase Database by Schlumberger (SLBDB Version 1.0)**
  - **13 Experimental Data Sets & 4,056 Data Records**
    - **Gas-Liquid Data Sets : 10 Sets (3,192 Records)**
    - **Oil-Water Data Sets : 1 (296 Records)**
    - **Gas-Oil-Water Data Sets : 2 (568 Records)**
- **FFPDB Version 1.1 (August 2013)**
  - **Addition to SLBDB Version 1.0**
  - **41 Data Sets & 9,649 Data Records**
    - **Gas-Liquid Data Sets : 29 Sets (6,990 Records)**
    - **Oil-Water Data Sets : 8 Sets (1,978 Records)**
    - **Gas-Oil-Water Data Sets : 4 Sets (681 Records)**

List of Data Sets

	Dataset	Year	Phase	No. of Records
SLBDB & FFPDB	Khor	1998	Gas-Oil-Water	412
	MukherjeeUp	1979	Gas-Liquid	634
	MukherjeeDn	1979	Gas-Liquid	634
	MukherjeeHor	1979	Gas-Liquid	132
	Minami	1987	Gas-Liquid	111
	Abdul	1994	Gas-Liquid	88
	Eaton	1966	Gas-Liquid	238
	Beggs	1973	Gas-Liquid	58
	Atmaca	2007	Oil-Water	296
	Dong	2007	Gas-Oil-Water	156
	Gokcal	2008	Gas-Liquid	173
	Magrini	2009	Gas-Liquid	140
	Johnson	2005	Gas-Liquid	984
	Total Number of Records			4056

	Dataset	Year	Phase	No. of Records
FFPDB	Ge Yuan	2011	Gas-Liquid	153
	Andritsos	1986	Gas-Liquid	535
	Beggs	1972	Gas-Liquid	188
	Cheremisinoff	1977	Gas-Liquid	174
	Kokal	1987	Gas-Liquid	140
	Rothe	1986	Gas-Liquid	39
	Fan	2005	Gas-Liquid	351
	Gokcal	2005	Gas-Liquid	183
	Kora	2009	Gas-Liquid	144
	Jeyachandra	2011	Gas-Liquid	350
	Yu	2009	Gas-Liquid	543
	Brito	2012	Gas-Liquid	346
	Meng	1999	Gas-Liquid	182
	Marcano	1996	Gas-Liquid	93
	Yang	1996	Gas-Liquid	90
	Brill et al.	1995	Gas-Liquid	48
	Felizola	1992	Gas-Liquid	89
	Roumazeilles	1994	Gas-Liquid	113
	Zheng	1989	Gas-Liquid	37
	Paredes	2007	Oil-Water	189
	Alkaya	2000	Oil-Water	282
	Flores	1997	Oil-Water	484
	Laflin and Oglesby	1976	Oil-Water	127
	Laflin and Oglesby	1976	Gas-Oil-Water	79
	Mukhopadhyay	1977	Oil-Water	114
	Oglesby	1979	Oil-Water	422
	Malinowski	1975	Oil-Water	64
	Malinowski	1975	Gas-Oil-Water	34
	Total Number of Records			5593

Data Base Variables

Gas-Liquid Variables

Variables	Units	Variables	Units
DataID	-	Flow Regime	-
PhaseID	-	Pressure Drop	Pa/m
Authors	-	Water Cut	-
Year Measured	-	Liquid Mix Superficial Velocity	m/s
System Pressure	Pa	Liquid Mix Hold Up	-
System Temperature	°C	Obs_emulsion	
Pipe Diameter	m	Transition Velocity	m/s
Pipe Roughness	m	Slug Liquid Hold Up	-
Pipe Inclination Angle	degree	Slug Frequency	1/s
Pipe Length	m	Film Hold Up	-
Gas Superficial Velocity	m/s	Slug Length	m
Gas Volume Flow Rate	m^3/s	Film Length	m
Gas Density	kg/m^3	Wetted Wall Fraction	-
Gas Viscosity	Pa·s	Entrainment	-
Gas-Liquid Surface Tension	N/m	Density Ratio	-
Gas-Liquid Ratio	-	Superficial Gas Reynolds Number	-
Gas Hold Up Measured	-	Superficial Liquid Reynolds Number	-
Liq1 Name	-	Reynolds Number	-
Liq1 Superficial Velocity	m/s	Quality	-
Liq1 Vol Flow Rate	m^3/s	Froud Number	-
Liq1 Density	kg/m^3	Superficial Gas Weber Number	-
Liq1 Viscosity	Pa·s	Friction Factor	-
Liq1 Surface Tension	N/m	Pressure Drop Multiplier	-
Liq1 Hold UP Measured	-		

Slug Flow Variables

Dimensionless Variables

FFPDB Additional Variables (Not in SLBDB)

Data Base Variables …

Oil-Water Variables

Variables	Units	Variables	Units
DataID	-	Liq1 Surface Tension	N/m
PhaseID	-	Liq1 Hold UP Measured	-
Authors	-	Liq2 Name	-
Year Measured	-	Liq2 Superficial Velocity	m/s
System Pressure	Pa	Liq2 Vol Flow Rate	m^3/s
System Temperature	°C	Liq2 Density	kg/m^3
Pipe Diameter	m	Liq2 Viscosity	Pa·s
Pipe Roughness	m	Liq2 Surface Tension	N/m
Pipe Inclination Angle	degree	Liq2 Hold UP Measured	-
Pipe Length	m	Flow Regime	-
Liq1 Name	-	Pressure Drop	Pa/m
Liq1 Superficial Velocity	m/s	Water Cut	-
Liq1 Vol Flow Rate	m^3/s	Liquid Mix Superficial Velocity	m/s
Liq1 Density	kg/m^3	Liquid Mix Hold Up	-
Liq1 Viscosity	Pa·s	Obs_emulsion	-

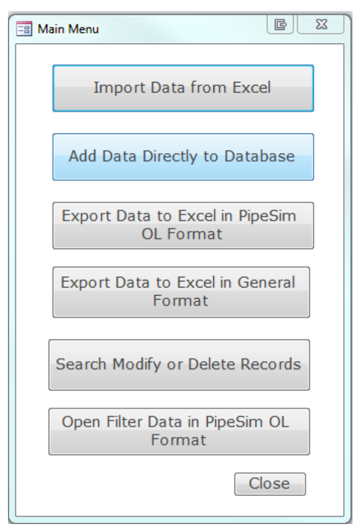
Data Base Variables …

- Gas-Oil-Water Variables

Variables	Units	Variables	Units
DataID	-	Liq1 Vol Flow Rate	m^3/s
PhaseID	-	Liq1 Density	kg/m^3
Authors	-	Liq1 Viscosity	Pa·s
Year Measured	-	Liq1 Surface Tension	N/m
System Pressure	Pa	Liq1 Hold UP Measured	-
System Temperature	°C	Liq2 Name	-
Pipe Diameter	m	Liq2 Superficial Velocity	m/s
Pipe Roughness	m	Liq2 Vol Flow Rate	m^3/s
Pipe Inclination Angle	degree	Liq2 Density	kg/m^3
Pipe Length	m	Liq2 Viscosity	Pa·s
Gas Superficial Velocity	m/s	Liq2 Surface Tension	N/m
Gas Volume Flow Rate	m^3/s	G_W Surface Tension	N/m
Gas Density	kg/m^3	Liq2 Hold UP Measured	-
Gas Viscosity	Pa·s	Flow Regime	-
Gas-Liquid Surface Tension	N/m	Pressure Drop	Pa/m
Gas-Liquid Ratio	-	Water Cut	-
Gas Hold Up Measured	-	Liquid Mix Superficial Velocity	m/s
Liq1 Name	-	Liquid Mix Hold Up	-
Liq1 Superficial Velocity	m/s	Obs_emulsion	-

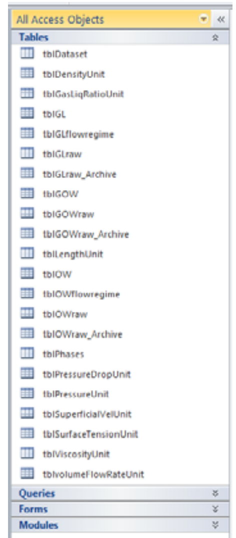
MS Access User Interface

- Main Menu (Form)
  - Default Pop-Up Form
  - Connection to Other Forms



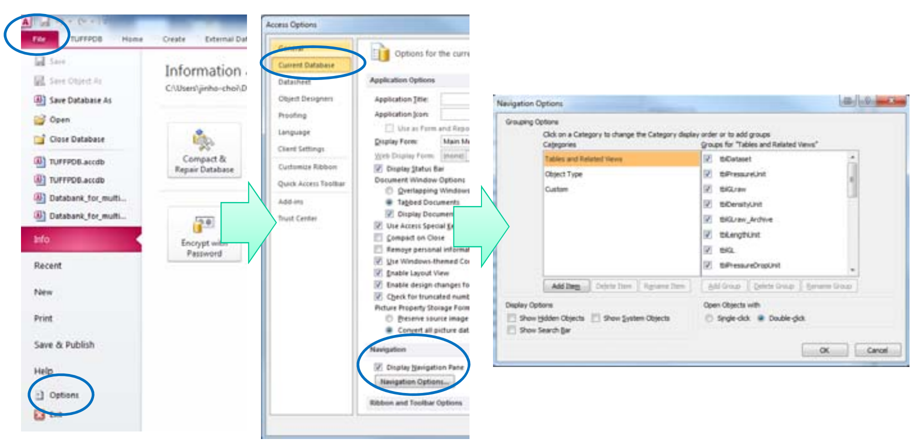
MS Access User Interface …

- Navigation Pane
  - List of All Access Objects
  - Tables, Queries, Forms, Modules



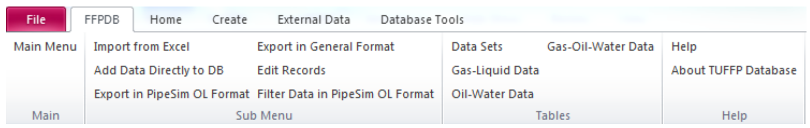
MS Access User Interface …

- Navigation Pane Setting



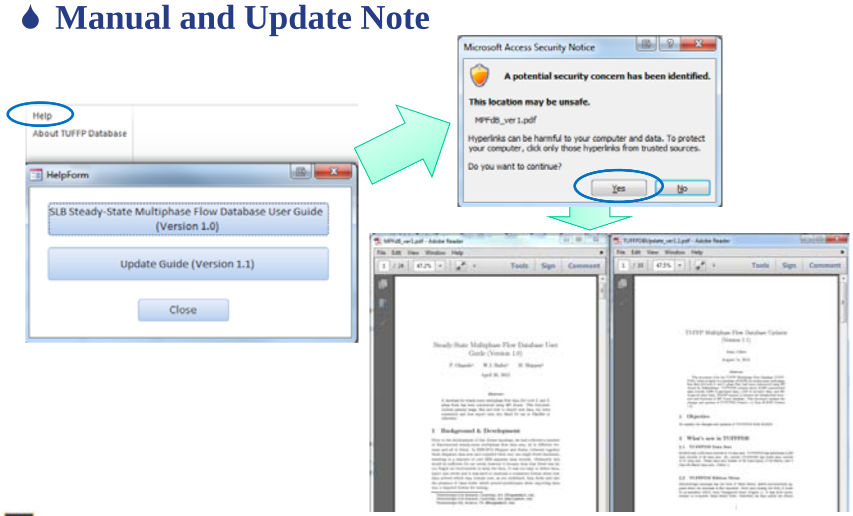
MS Access User Interface …

- Ribbon Menu
  - Open Major Forms and Tables
  - Link to Open SLBDB Manual and FFPDB Update Note



MS Access User Interface …

- Manual and Update Note

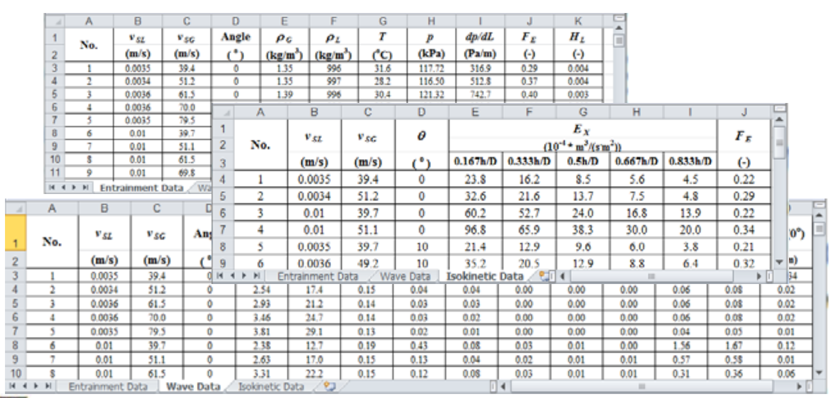


Data Quality Control

- **Raw Data Stage**
  - **Copy Raw Data Sets to Formatted *Excel* File**
    - **New *Excel* File for New Data Set**
    - **Save *Excel* File As Specific File Name To Identify Data Set**
  - **Check All or Randomly Copied Data Records of *Excel* File Comparing to Raw Data**
- **Database Table Stage**
  - **Import Raw Data Sets From *Excel* File to *Access* Master Data Table**
    - ***Excel* Raw Data File → *Access* Raw Data Table → *Access* Archive Data Table → *Access* Master Data Table**
  - **Convert Units of Checked *Excel* File Raw Data in SI Units**
  - **Check All or Random Data of *Access* Master Table Comparing to Unit Converted *Excel* File Raw Data**

Data Import and Export Demonstration

- **Data Import**
  - **Magrini, 2009**
    - **Data Given in Excel File**



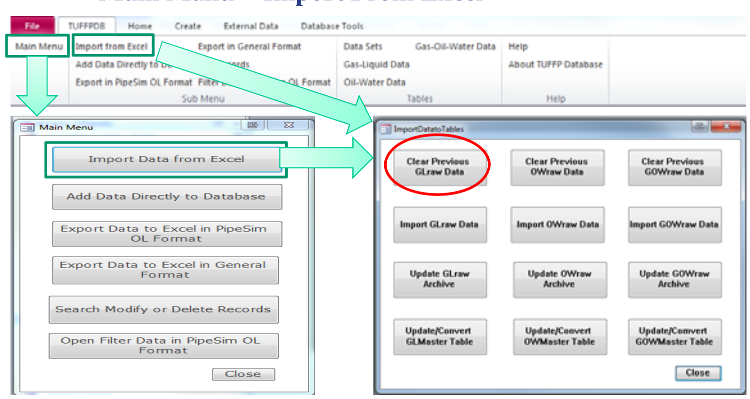
Data Import and Export Demonstration …

- **Data Import …**
  - **Preparation of Formatted Excel File**
    - **Save As…"GL_ImportHeadingFormat - TUFFP113.xlsx"**

	A	B	C	D	E	F	G	H	I	J	
1	AuthorsGLraw	YearMeasuredGLraw	SystPressureGLraw	SystPresGLrawUnit	SystTempGLraw/C	PipeDiaGLraw	ipeDiaGLrawUn	PipeRoughGLraw	ipeRoughGLrawUn	PipeIncliGLraw	Pi
2	Magrini	2009	117.7195002	4	31.62222222	0.0762	1	0	1	0	
3	Magrini	2009	116.4991	4	28.16666667	0.0762	1	0	1	0	
4	Magrini	2009	121.3228	4	30.44444444	0.0762	1	0	1	0	
5	Magrini	2009	120.4257	4	29.66111111	0.0762	1	0	1	0	
6	Magrini	2009	121.2451	4	30.11111111	0.0762	1	0	1	0	
7	Magrini	2009	118.4696	4	31.46111111	0.0762	1	0	1	0	
8	Magrini	2009	117.0763	4	30.31111111	0.0762	1	0	1	0	
9	Magrini	2009	121.4514	4	29.31666667	0.0762	1	0	1	0	
10	Magrini	2009	121.5363	4	29.12222222	0.0762	1	0	1	0	
11	Magrini	2009	121.4519	4	29.06666667	0.0762	1	0	1	0	
12	Magrini	2009	119.3443	4	32.91111111	0.0762	1	0	1	0	
13	Magrini	2009	118.0203	4	32.28888889	0.0762	1	0	1	0	
14	Magrini	2009	122.7209	4	30.68888889	0.0762	1	0	1	0	
15	Magrini	2009	122.4598	4	30.50555556	0.0762	1	0	1	0	
16	Magrini	2009	122.8309	4	30.45	0.0762	1	0	1	0	
17	Magrini	2009	119.9601	4	33.18888889	0.0762	1	0	1	0	
18	Magrini	2009	119.978	4	33.98333333	0.0762	1	0	1	0	
19	Magrini	2009	126.9517	4	33.31111111	0.0762	1	0	1	0	
20	Magrini	2009	117.4805	4	32.93333333	0.0762	1	0	1	0	
21	Magrini	2009	122.8998	4	33.79444444	0.0762	1	0	1	0	
22	Magrini	2009	120.6068218	4	26.66666667	0.0762	1	0	1	10	
23	Magrini	2009	114.0811325	4	31.48888889	0.0762	1	0	1	10	
24	Magrini	2009	119.3741476	4	27.92222222	0.0762	1	0	1	10	

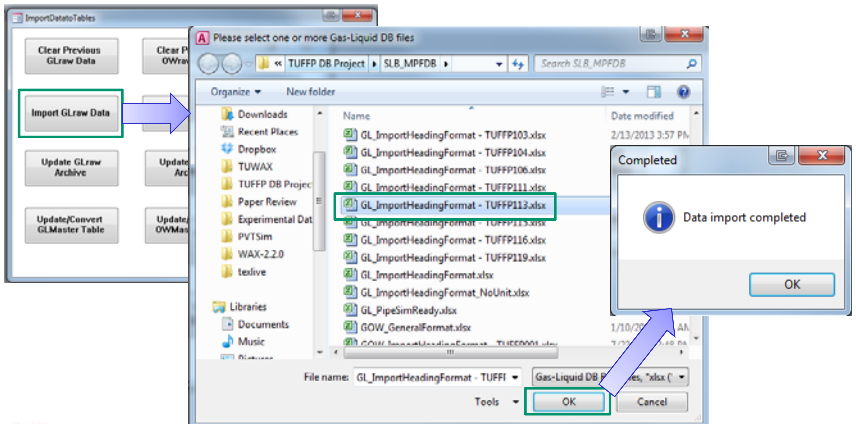
Data Import and Export Demonstration …

- **Data Import …**
  - **Clearing Previously Imported Raw Data**
    - **Main Manu > Import From Excel**



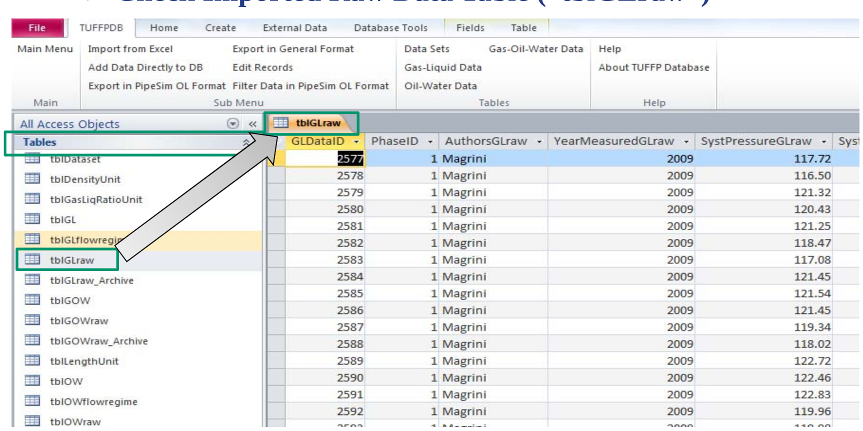
Data Import and Export Demonstration …

- **Data Import …**
  - **Import GLraw Data**



Data Import and Export Demonstration …

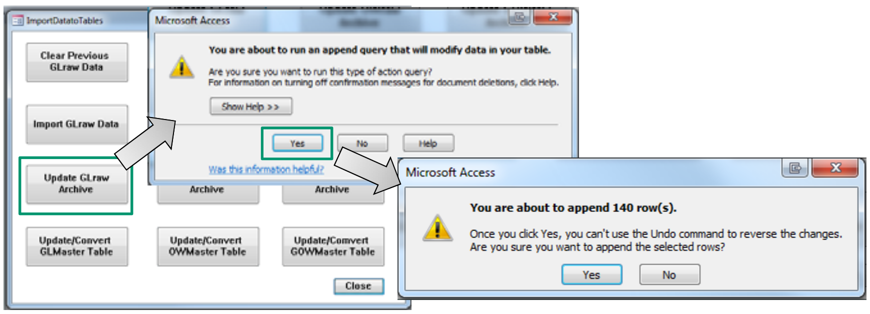
- **Data Import …**
  - **Check Imported Raw Data Table ("tblGLraw")**



GLDataID	PhaseID	AuthorsGLraw	YearMeasuredGLraw	SystPressureGLraw
2577	1	Magrini	2009	117.72
2578	1	Magrini	2009	116.50
2579	1	Magrini	2009	121.32
2580	1	Magrini	2009	120.43
2581	1	Magrini	2009	121.25
2582	1	Magrini	2009	118.47
2583	1	Magrini	2009	117.08
2584	1	Magrini	2009	121.45
2585	1	Magrini	2009	121.54
2586	1	Magrini	2009	121.45
2587	1	Magrini	2009	119.34
2588	1	Magrini	2009	118.02
2589	1	Magrini	2009	122.72
2590	1	Magrini	2009	122.46
2591	1	Magrini	2009	122.83
2592	1	Magrini	2009	119.96

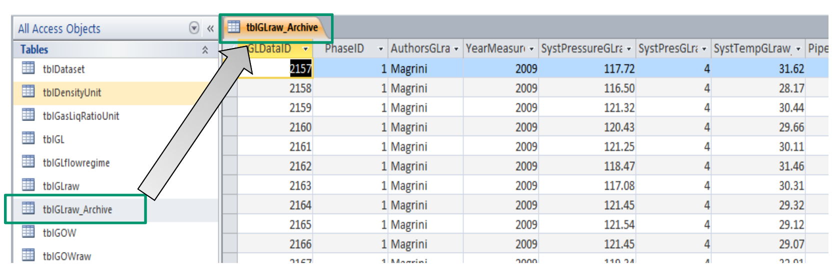
Data Import and Export Demonstration …

- **Data Import …**
  - **Update GLraw Archive (*Optional*)**



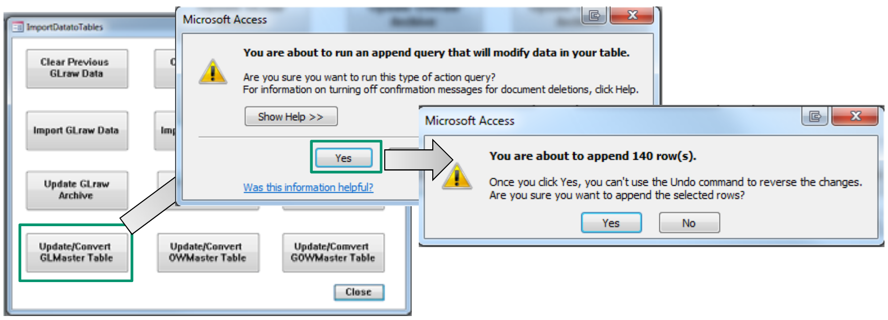
Data Import and Export Demonstration …

- **Data Import …**
  - **Check GLraw Archive Table ("tblGLraw_Archive")**



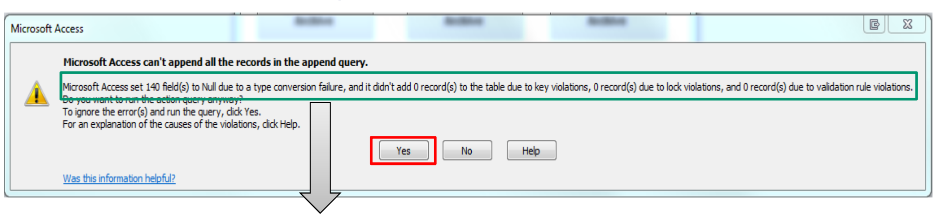
Data Import and Export Demonstration …

- Data Import …
  - Update/Convert GL Master Table



Data Import and Export Demonstration …

- Data Import …
  - Update/Convert GL Master Table …
    - Error Message

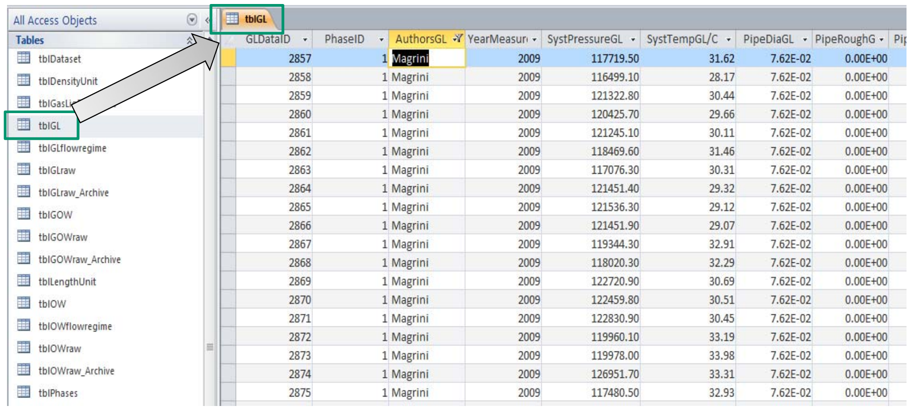


140 field(s) to Null due to a type conversion failure,
and it **did not add 0** record(s) to the table due to key violations,
0 record(s) due to lock violations, and **0** record(s) due to validation rule violations.

→ **It Adds All Data Records to the Table.**

Data Import and Export Demonstration …

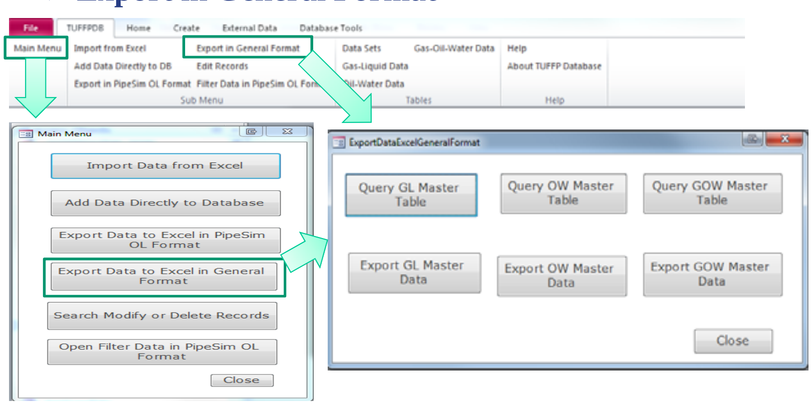
- **Data Import …**
  - **Check GL Master Table**



GLDataID	PhaseID	AuthorsGL	YearMeasur	SystPressureGL	SystTempGL/C	PipeDiaGL	PipeRoughG	Pi
2857	1	Magrini	2009	117719.50	31.62	7.62E-02	0.00E+00	
2858	1	Magrini	2009	116499.10	28.17	7.62E-02	0.00E+00	
2859	1	Magrini	2009	121322.80	30.44	7.62E-02	0.00E+00	
2860	1	Magrini	2009	120425.70	29.66	7.62E-02	0.00E+00	
2861	1	Magrini	2009	121245.10	30.11	7.62E-02	0.00E+00	
2862	1	Magrini	2009	118469.60	31.46	7.62E-02	0.00E+00	
2863	1	Magrini	2009	117076.30	30.31	7.62E-02	0.00E+00	
2864	1	Magrini	2009	121451.40	29.32	7.62E-02	0.00E+00	
2865	1	Magrini	2009	121536.30	29.12	7.62E-02	0.00E+00	
2866	1	Magrini	2009	121451.90	29.07	7.62E-02	0.00E+00	
2867	1	Magrini	2009	119344.30	32.91	7.62E-02	0.00E+00	
2868	1	Magrini	2009	118020.30	32.29	7.62E-02	0.00E+00	
2869	1	Magrini	2009	122720.90	30.69	7.62E-02	0.00E+00	
2870	1	Magrini	2009	122459.80	30.51	7.62E-02	0.00E+00	
2871	1	Magrini	2009	122830.90	30.45	7.62E-02	0.00E+00	
2872	1	Magrini	2009	119960.10	33.19	7.62E-02	0.00E+00	
2873	1	Magrini	2009	119978.00	33.98	7.62E-02	0.00E+00	
2874	1	Magrini	2009	126951.70	33.31	7.62E-02	0.00E+00	
2875	1	Magrini	2009	117480.50	32.93	7.62E-02	0.00E+00	

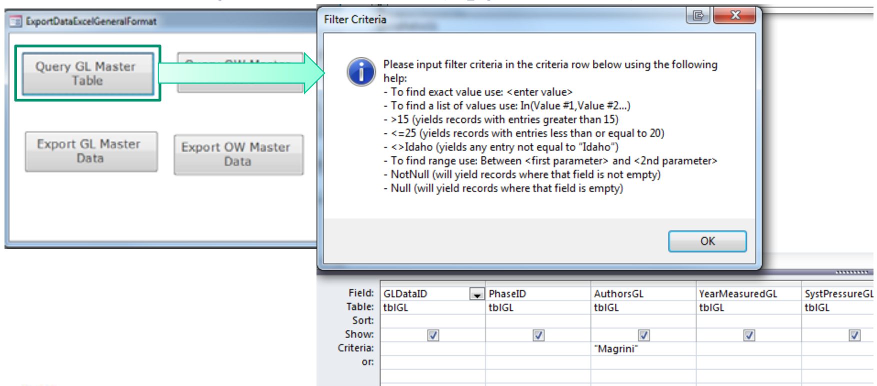
Data Import and Export Demonstration …

- **Data Export …**
  - **Export in General Format**



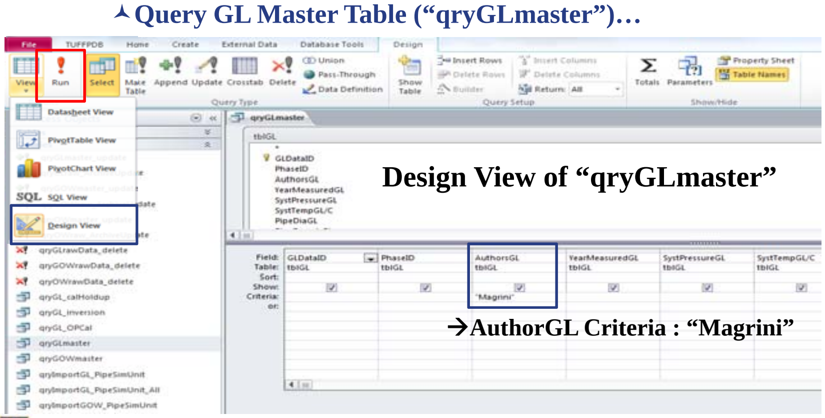
Data Import and Export Demonstration …

- Data Export …
  - Export in General Format …
    - Query GL Master Table ("qryGLmaster")



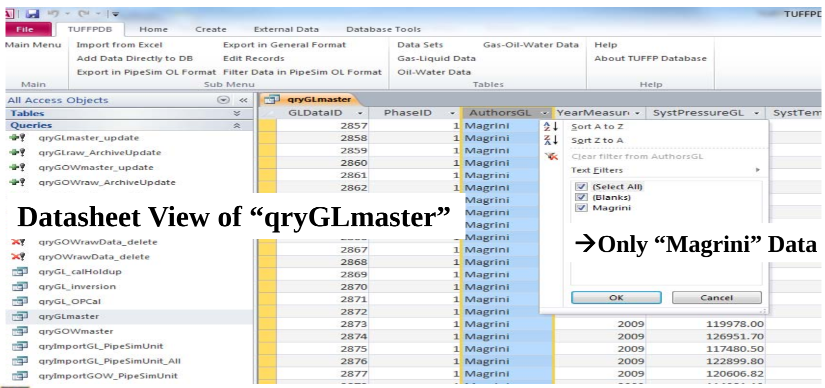
Data Import and Export Demonstration …

- Data Export …
  - Export in General Format…
    - Query GL Master Table ("qryGLmaster")…



Data Import and Export Demonstration …

- **Data Export …**
  - **Export in General Format…**
    - **Query GL Master Table (“qryGLmaster”)…**

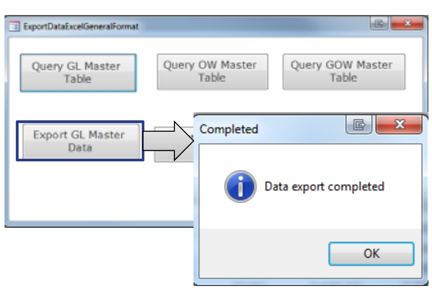


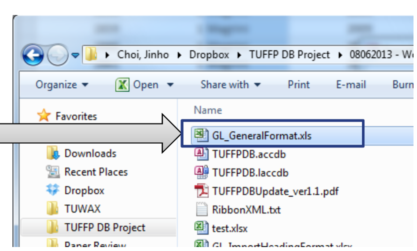
Datasheet View of “qryGLmaster”

→Only “Magrini” Data

Data Import and Export Demonstration …

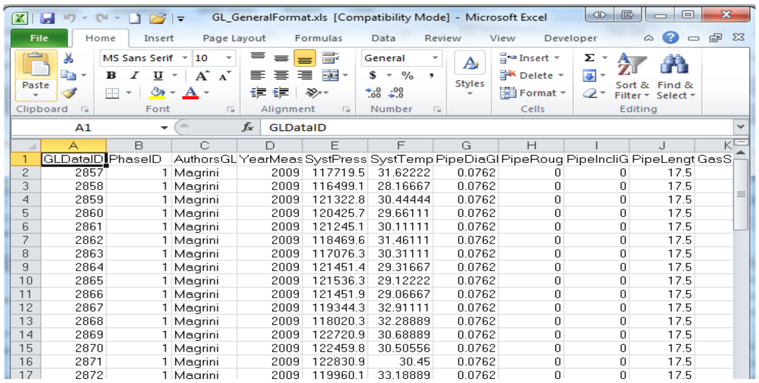
- **Data Export …**
  - **Export in General Format…**
    - **Export GL Master Data**
      - **Automatically Saved As “GL_GeneralFormat.xls” Under Same File Location of Database**





Data Import and Export Demonstration…

- **Data Export …**
  - **Export in General Format…**
    - **Check Exported GL Master Data**

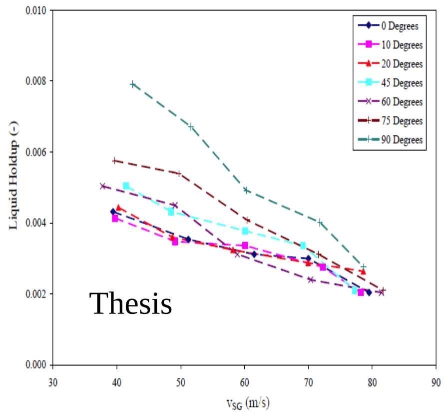


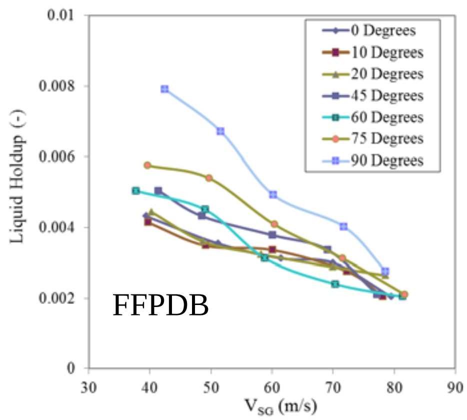
GL_GeneralFormat.xls [Compatibility Mode] - Microsoft Excel

	A	B	C	D	E	F	G	H	I	J	K
1	GLDataID	PhaseID	AuthorsGL	YearMeas	SystPress	SystTemp	PipeDiaGl	PipeRoug	PipeIncliG	PipeLengt	GasS
2	2857	1	Magrini	2009	117719.5	31.62222	0.0762	0	0	17.5	
3	2858	1	Magrini	2009	116499.1	28.16667	0.0762	0	0	17.5	
4	2859	1	Magrini	2009	121322.8	30.44444	0.0762	0	0	17.5	
5	2860	1	Magrini	2009	120425.7	29.66111	0.0762	0	0	17.5	
6	2861	1	Magrini	2009	121245.1	30.11111	0.0762	0	0	17.5	
7	2862	1	Magrini	2009	118469.6	31.46111	0.0762	0	0	17.5	
8	2863	1	Magrini	2009	117076.3	30.31111	0.0762	0	0	17.5	
9	2864	1	Magrini	2009	121451.4	29.31667	0.0762	0	0	17.5	
10	2865	1	Magrini	2009	121536.3	29.12222	0.0762	0	0	17.5	
11	2866	1	Magrini	2009	121451.9	29.06667	0.0762	0	0	17.5	
12	2867	1	Magrini	2009	119344.3	32.91111	0.0762	0	0	17.5	
13	2868	1	Magrini	2009	118020.3	32.28889	0.0762	0	0	17.5	
14	2869	1	Magrini	2009	122720.9	30.68889	0.0762	0	0	17.5	
15	2870	1	Magrini	2009	122459.8	30.50556	0.0762	0	0	17.5	
16	2871	1	Magrini	2009	122830.9	30.45	0.0762	0	0	17.5	
17	2872	1	Magrini	2009	119960.1	33.18889	0.0762	0	0	17.5	

Data Import and Export Demonstration …

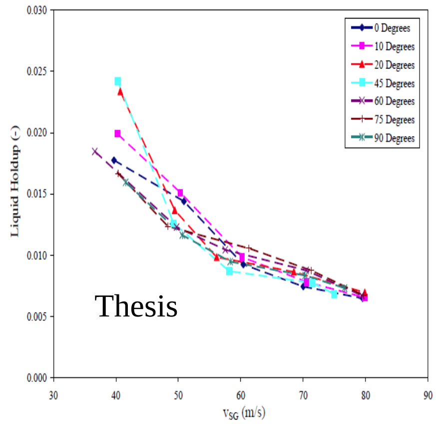
- **Data Quality Check**
  - **Gas Superficial Velocity vs. Liquid Holdup (V_{SL} = 0.0035 m/s)**

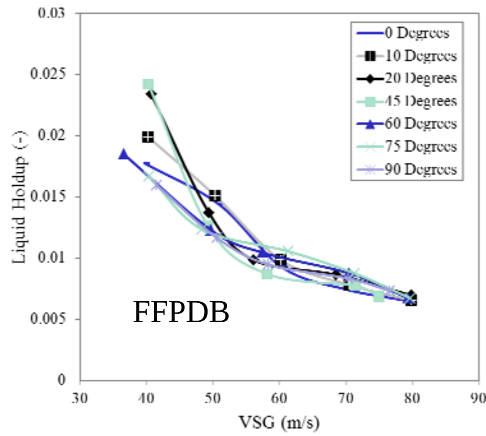




Data Import and Export Demonstration…

- **Data Quality Check …**
  - **Gas Superficial Velocity vs. Liquid Holdup (V_{SL} = 0.04 m/s)**





Fluid Flow Projects

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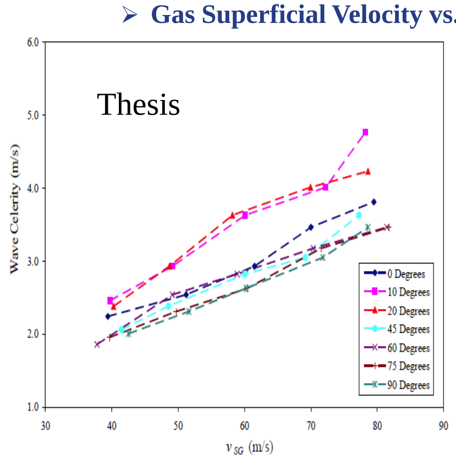
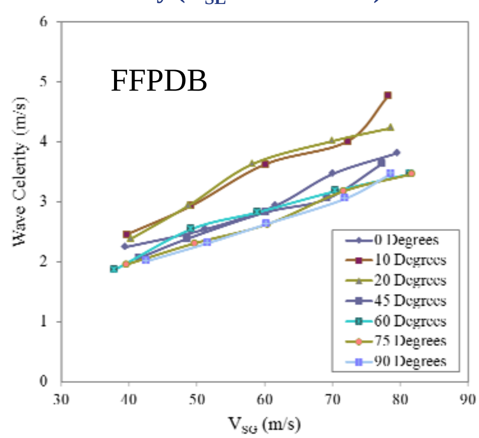
Data Import and Export Demonstration …

- **Data Quality Check …**
  - **Gas Superficial Velocity vs. Wave Celerity (V_{SL} = 0.0035 m/s)**





Fluid Flow Projects

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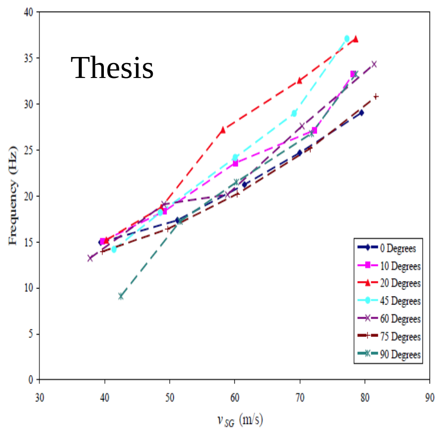
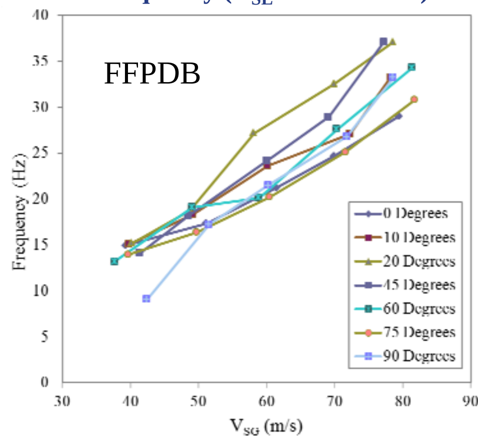
Data Import and Export Demonstration …

- **Data Quality Check …**
  - **Gas Superficial Velocity vs. Wave Frequency (V_{SL} = 0.0035 m/s)**





Fluid Flow Projects

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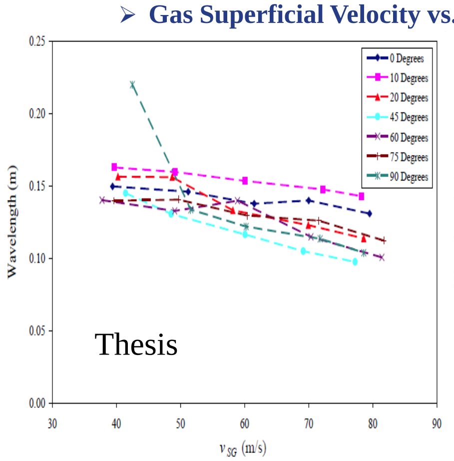
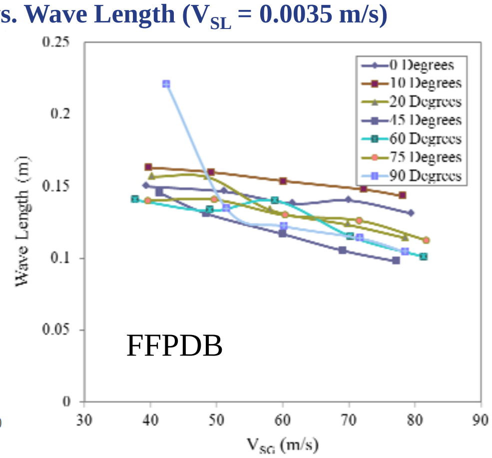
Data Import and Export Demonstration …

- **Data Quality Check …**
  - **Gas Superficial Velocity vs. Wave Length (V_{SL} = 0.0035 m/s)**





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Future Work

- Import More Experimental or Field Data
- Recheck Data Integrity
  - Complete Missing or Not Provided Variables
- Development of Filtered Data Export Form
- Improvement of Overall User Interface

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Thank you for listening!

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TUFFP Experimental Database

Jinho Choi

Project Completion Dates

Objectives

The main objective of this project is to construct a multiphase flow database of TUFFP experimental data sets.

Introduction

The TUFFP experimental database contains the measurements of various parameters including pressures, pressure gradients, volume fractions, shear stresses, entrainment fractions, and the system parameters associated with each run. In some instances, additional data like individual flow pattern characteristics are also included.

Usually, experimental data sets have their own specific formats. Moreover, they are sometimes provided as tables in pdf format, which need to be digitized. Having all of the experimental data sets in a unified format makes the experimental data more usable and applicable. In other words, the database can be easily used to validate newly developed models for multiphase flow, by exporting data into required formats for testing.

Steady-State Multiphase Database by Schlumberger (Version 1.0)

Schlumberger developed the steady-state multiphase database using Microsoft Access, which was donated to TUFFP. Schlumberger selected MS Access to replace the MS Excel database. MS Excel is easy to use and easy to access, but it has limitations for databases. It is too fragile to store the data, too easy to delete data, too easy to inject unit errors, and difficult to maintain a consistent format. New or undefined data fields may destroy the existing format and lead to 'data holes'. Furthermore, MS Excel can be problematic when exporting data into required formats for testing.

The Schlumberger multiphase steady-state database (SLBDB) can import experimental data records with a specific format. Data records are initially imported into a 'Raw Table' from the formatted Excel file. The data records of the 'Raw Table' move to a final 'Database Table' after unit conversions through the 'Raw Archive Table'. The database can export data records to Excel files in PipeSim OpenLink format or in general format.

FFPDB (Version 1.1)

SLBDB (Version 1.0) has been modified and improved. It is named 'FFPDB' and updated to 'Version 1.1'. Major changes of FFPDB are an increased number of data sets, additional variables, unit setting of Gas-Liquid raw data files, and user interface.

Data Sets

At present, FFPDB has 41 experimental data sets with 9,649 data records; SLBDB had 13 data sets with 4,056 data records. The data sets and number of records are given in Table 1. The database consists of 29 Gas-Liquid data sets, 8 Oil-Water data sets, and 4 Gas-Oil-Water data sets. Their data records are 6,990, 1,978, and 681, respectively.

Additional Variables

In the Gas-Liquid database, additional variable columns had been added for FFPDB. Those columns are for slug flow characteristics and dimensionless variables. The Oil-Water and Gas-Oil-Water databases have not been modified yet. Original and additional variables of the Gas-Liquid database table are given in Table 2.

Unit Setting of Gas-Liquid Raw Data File

SLBDB has a stage to set the units of variables during data importing. If the number of data records is plentiful, this stage is extremely inconvenient. The user needs to click as many as the number of variables multiplied by the number of data records. Copy and paste does not work for this procedure. For FFPDB, the unit setting columns are added to the formatted Excel file for Gas-Liquid data. This makes the Gas-Liquid data import procedure faster and more convenient.

User Interface

When DB is launched, the 'Main Menu' form (Figure 1) appears. This form allows access to all other major forms, which have buttons for DB functions. There are 6 major forms as shown on the 'Main Menu' form: 'Import from Excel', 'Add Data Directly to DB', 'Export in PipeSim OL Format', 'Export in General Format', and 'Filter Data in PipeSim OL Format'. In SLBDB, the 'Main Menu' form can only be re-launched from the 'Navigation pane' (Figure 2) after being closed. The 'Navigation pane' shows the list of all tables, queries, forms, modules. Re-launching the 'Main Menu' or other forms from the navigation pane is inconvenient. FFPDB has a ribbon menu (Figure 3) to access all major forms, major tables, and DB manuals. The ribbon menu helps the user access forms and tables more conveniently.

Update Notes

SLBDB provided a PDF manual file named 'MPFdB_ver1.pdf'. This manual can be opened from the help menu of the FFPDB ribbon menu.

The FFPDB update notes file, which is named 'FFPDBUpdate_ver1.1.pdf', can also be opened from the help menu. It includes the detailed explanations mentioned in this report.

Future Work

More available data records will be imported into FFPDB.Addtionally, the overall user interface will be improved for more convenience. Notably, the filtered data export form will be developed into an intuitive form. Currently, it is using a MS Access query.

Table 1. List of Data Sets and Number of Data Records

	Dataset	Year	Phase	No. of Records
SLBDB & TUFFPDB	Khor	1998	Gas-Oil-Water	412
	MukherjeeUp	1979	Gas-Liquid	634
	MukherjeeDn	1979	Gas-Liquid	634
	MukherjeeHor	1979	Gas-Liquid	132
	Minami	1987	Gas-Liquid	111
	Abdul	1994	Gas-Liquid	88
	Eaton	1966	Gas-Liquid	238
	Beggs	1973	Gas-Liquid	58
	Atmaca	2007	Oil-Water	296
	Dong	2007	Gas-Oil-Water	156
	Gokcal	2008	Gas-Liquid	173
	Magrini	2009	Gas-Liquid	140
	Johnson	2005	Gas-Liquid	984
	Total Number of Records			4056
TUFFPDB	Dataset	Year	Phase	No. of Records
	Ge Yuan	2011	Gas-Liquid	153
	Andritsos	1986	Gas-Liquid	535
	Beggs	1972	Gas-Liquid	188
	Cheremisinoff	1977	Gas-Liquid	174
	Kokal	1987	Gas-Liquid	140
	Rothe	1986	Gas-Liquid	39
	Fan	2005	Gas-Liquid	351
	Gokcal	2005	Gas-Liquid	183
	Kora	2009	Gas-Liquid	144
	Jeyachandra	2011	Gas-Liquid	350
	Yu	2009	Gas-Liquid	543
	Brito	2012	Gas-Liquid	346
	Meng	1999	Gas-Liquid	182
	Marcano	1996	Gas-Liquid	93
	Yang	1996	Gas-Liquid	90
	Brill et al.	1995	Gas-Liquid	48
	Felizola	1992	Gas-Liquid	89
	Roumazeilles	1994	Gas-Liquid	113
	Zheng	1989	Gas-Liquid	37
	Paredes	2007	Oil-Water	189
	Alkaya	2000	Oil-Water	282
	Flores	1997	Oil-Water	484
	Laflin and Oglesby	1976	Oil-Water	127
	Laflin and Oglesby	1976	Gas-Oil-Water	79
	Mukhopadhyay	1977	Oil-Water	114
	Oglesby	1979	Oil-Water	422
	Malinowski	1975	Oil-Water	64
	Malinowski	1975	Gas-Oil-Water	34
	Total Number of Records			5593

Table 2. Original and Additional Variables of Gas-Liquid Database Table

Variables	Units	Variables	Units
DataID	-	Flow Regime	-
PhaseID	-	Pressure Drop	Pa/m
Authors	-	Water Cut	-
Year Measured	-	Liquid Mix Superficial Velocity	m/s
System Pressure	Pa	Liquid Mix Hold Up	-
System Temperature	°C	Obs_emulsion	-
Pipe Diameter	m	Transition Velocity	m/s
Pipe Roughness	m	Slug Liquid Hold Up	-
Pipe Inclination Angle	degree	Slug Frequency	1/s
Pipe Length	m	Film Hold Up	-
Gas Superficial Velocity	m/s	Slug Length	m
Gas Volume Flow Rate	m^3/s	Film Length	m
Gas Density	kg/m^3	Wetted Wall Fraction	-
Gas Viscosity	Pa·s	Entrainment	-
Gas-Liquid Surface Tension	N/m	Density Ratio	-
Gas-Liquid Ratio	-	Superficial Gas Reynolds Number	-
Gas Hold Up Measured	-	Superficial Liquid Reynolds Number	-
Liq1 Name	-	Reynolds Number	-
Liq1 Superficial Velocity	m/s	Quality	-
Liq1 Vol Flow Rate	m^3/s	Froud Number	-
Liq1 Density	kg/m^3	Superficial Gas Weber Number	-
Liq1 Viscosity	Pa·s	Friction Factor	-
Liq1 Surface Tension	N/m	Pressure Drop Multiplier	-
Liq1 Hold UP Measured	-		

Slug Flow Variables

Dimensionless Variables

TUFFPDB Additional Variables (Not in SLBDB)

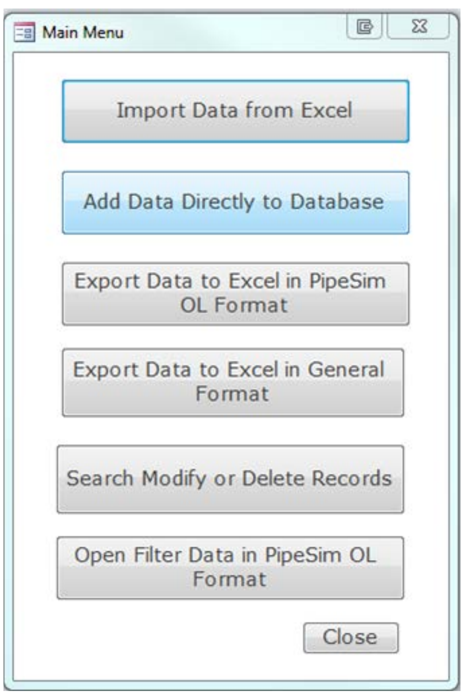

Figure 1. Main Menu Form

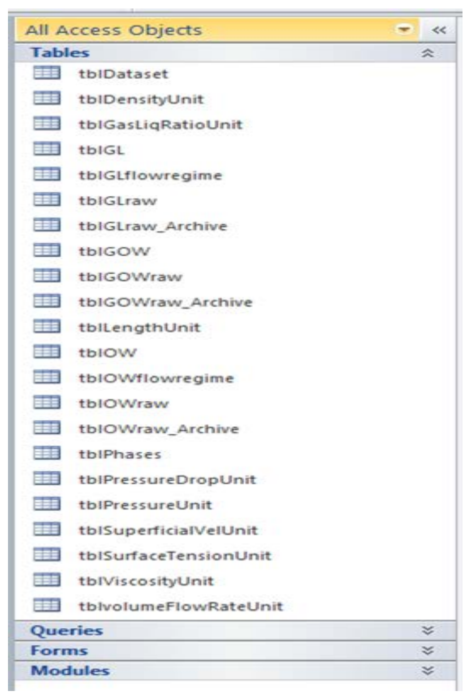

Figure 2. Navigation Pane

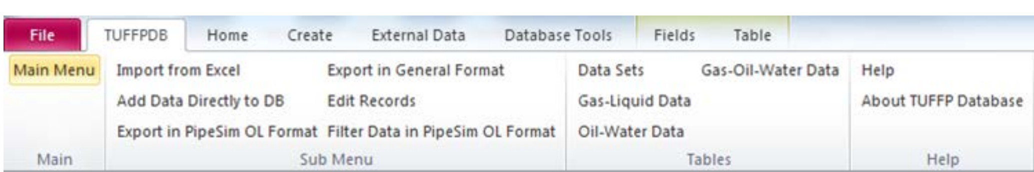

Figure 3. TUFFPDB Ribbon Menu

Fluid Flow Projects

Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Pipes

Feras Alruhaimani

Advisory Board Meeting, September 25, 2013

Outline

- Objectives
- Facility
- Test Fluid
- Test Matrix
- Calibrations
- Data Gathering & Processing
- Future Activities

Objectives

- Conduct Experimental and Modeling Study on High Oil Viscosity (>180 cP) Two-Phase Flow in Vertical Pipes
- Improve Existing Closure Relationships Used in Available Mechanistic Models

Fluid Flow Projects

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Three-Phase Flow Facility

Fluid Flow Projects

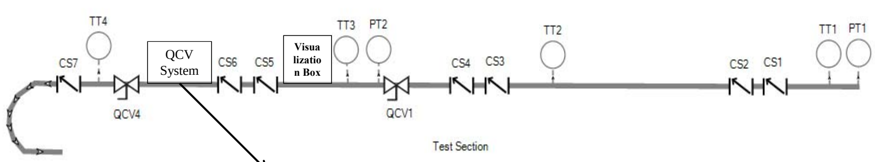
Advisory Board Meeting, September 25, 2013

Three-Phase Flow Facility …

- **Test Section**
  - **Two (2-in. ID) 21.5-m (70.4-ft) Long Pipes Connected with U-shaped Bend**

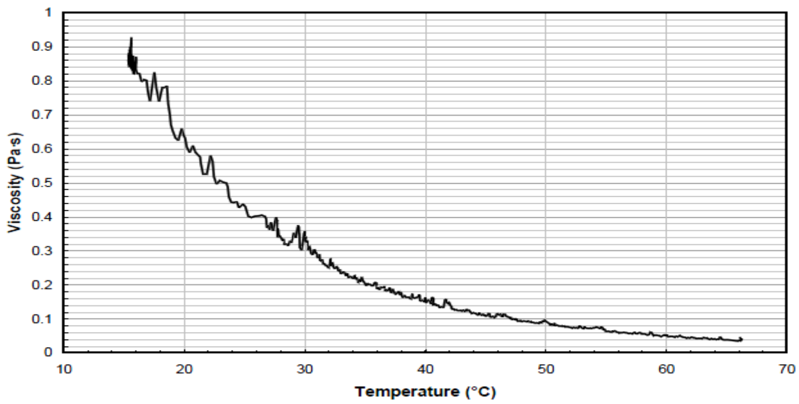
Three-Phase Flow Facility …

- **Test Section**



Test Fluids

- Lubsoil ND 50 (ISO 220)

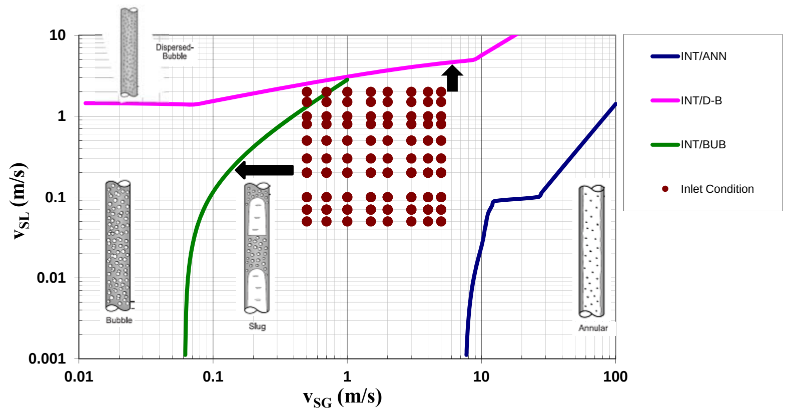


Test Matrix

- Viscosity
  - 181 – 587 cP
- Superficial Liquid Velocity
  - 0.05 – 2 m/s
- Superficial Gas Velocity
  - 0.5 – 5 m/s

Flow Pattern

μ = 378 cp , θ = 90º

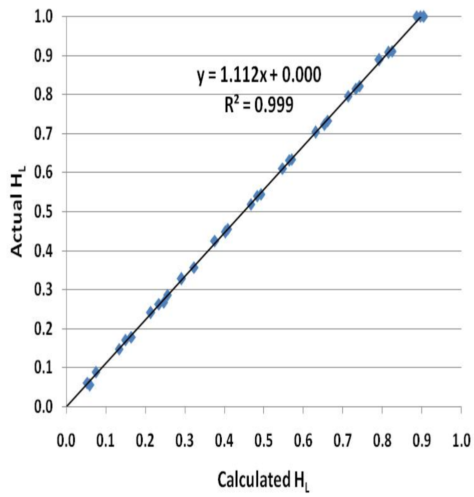


Calibrations

- Differential Pressure-Inclination Angle Zero Correction
- Quick-Closing Valves Speeds
- Capacitance Sensors Calibration
- Quick-Closing Valve System Calibration
- Long QCV Section Calibration

QCV System Calibration

- Quick-Closing Valve System (QCVS) will be used to trap:
  - Slug to Determine Slug Liquid Holdup
  - Film to Determine Film Liquid Holdup



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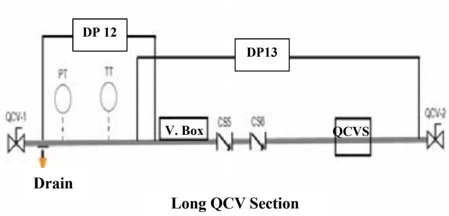
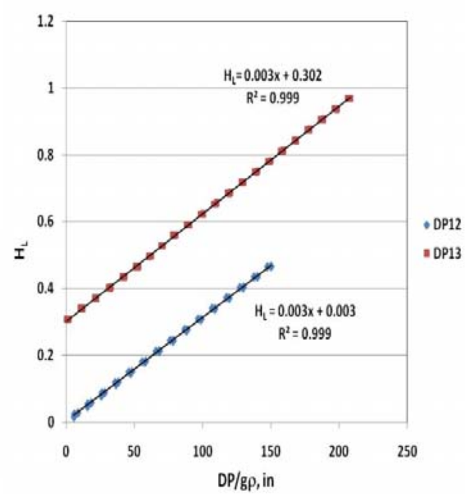
Long QCV Section Calibration

- Long QCV Section is 8.2-m (26.8-ft) Long Section Between Two QCVs





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Data Gathering & Processing

Low-Speed Data (1 to 10 Hz)

- Pressure
- Pressure Gradient
- Temperature
- Mass Flow Rates
- Densities
- Viscosities
- Superficial Velocities

High-Speed Data (1000 Hz) "Capacitance Sensors"

- Translation Velocity
- Average Slug Length
- Slug Length Distribution
- Slug Frequency
- Slug Liquid Holdup
- Film Liquid Holdup
- Average Liquid Holdup

Videos

- Digital
- High-Speed

Low-Speed Data

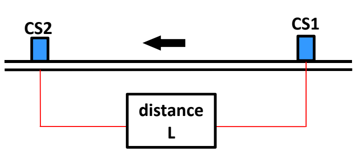
- A Matlab Macro has been Created to Calculate Average and Uncertainty for All The Low-Speed Raw Data
- Uncertainty is Calculated Using ISO Uncertainty Model

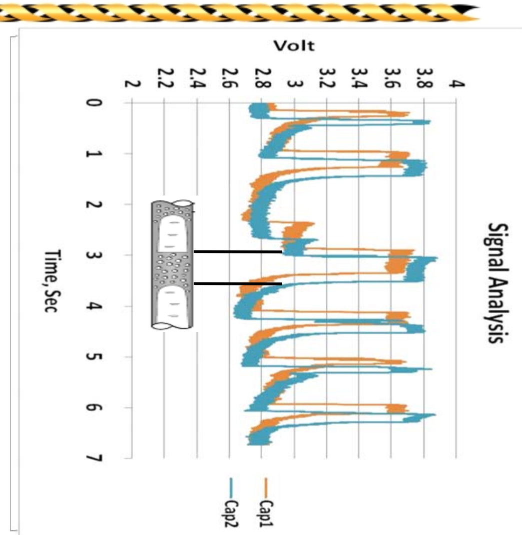
High-Speed Data

- High-Speed Data is Required for Slug Characterization
- A Matlab Macro has been Created to Process Capacitance Sensor Signals
- Matlab Macro Tested with Data from Brito (2012)

High-Speed Signal Processing

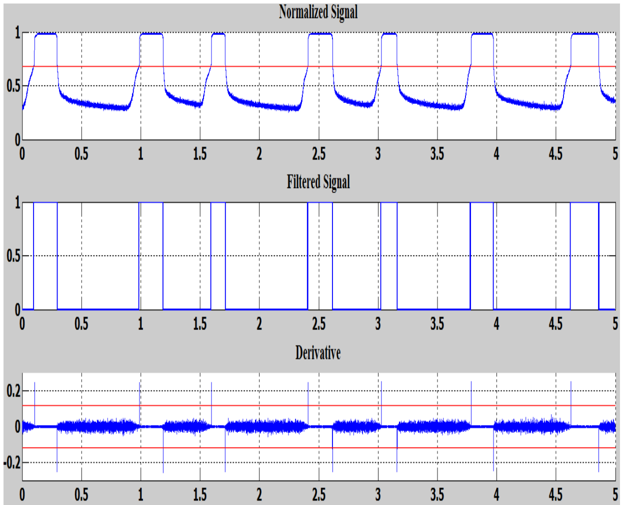
- 2 Capacitance Sensors





High-Speed Signal Processing …

- **Slug Region Identification**
  - Threshold
  - Derivative



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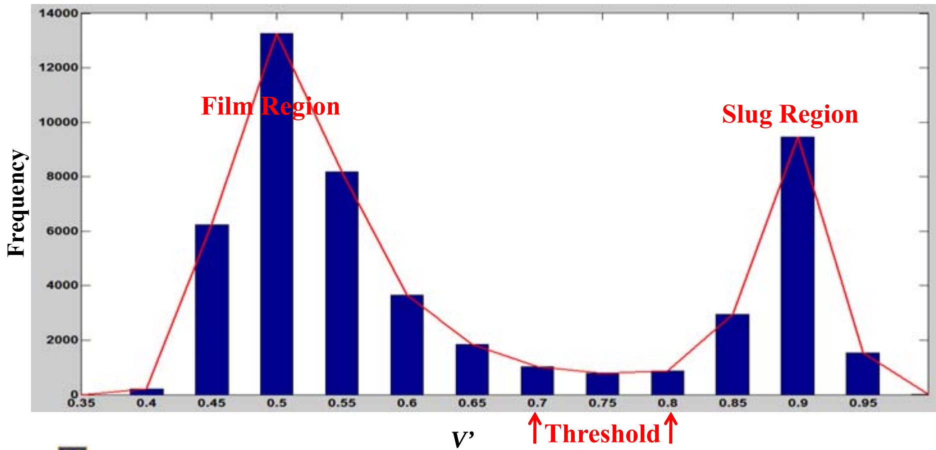
High-Speed Signal Processing …

- **Threshold Selection**



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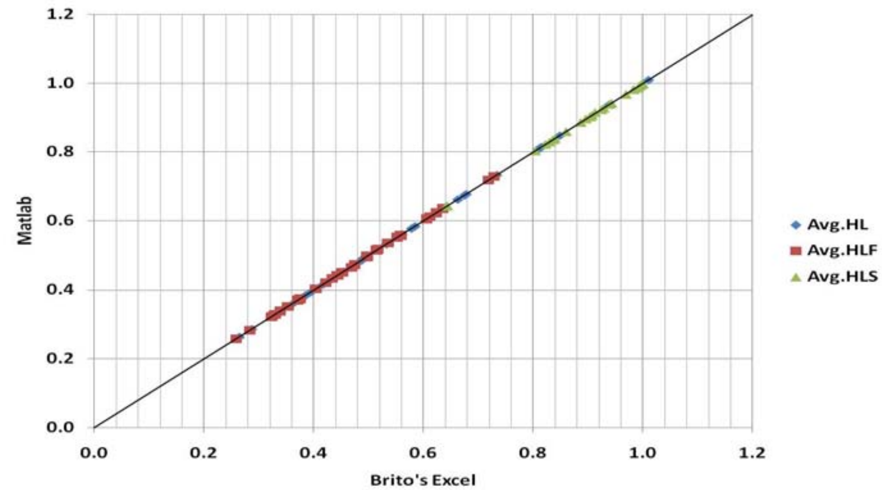
Comparison to Brito (Liquid Holdups)



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Comparison to Brito …

- Matlab Macros To Excel (Brito, 2012) Comparisons Show Consistency
- Matlab is More Suitable Than Excel as It Can Handle All Gathered Data

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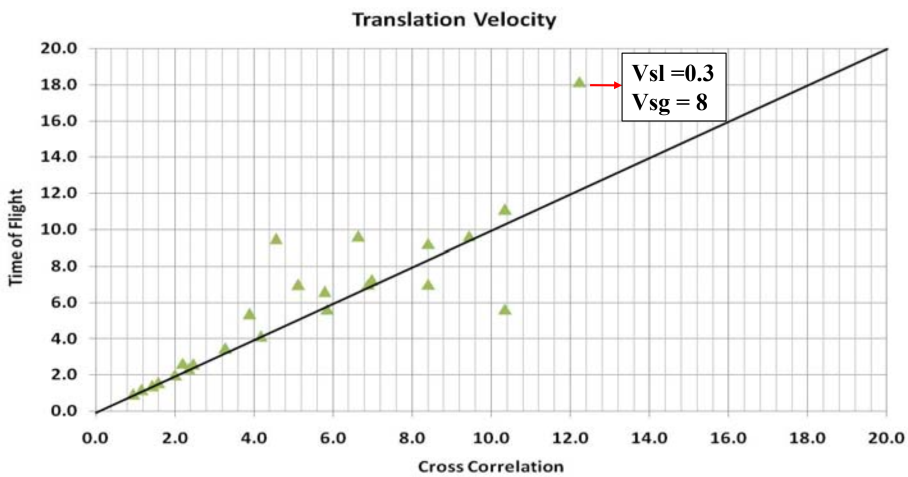
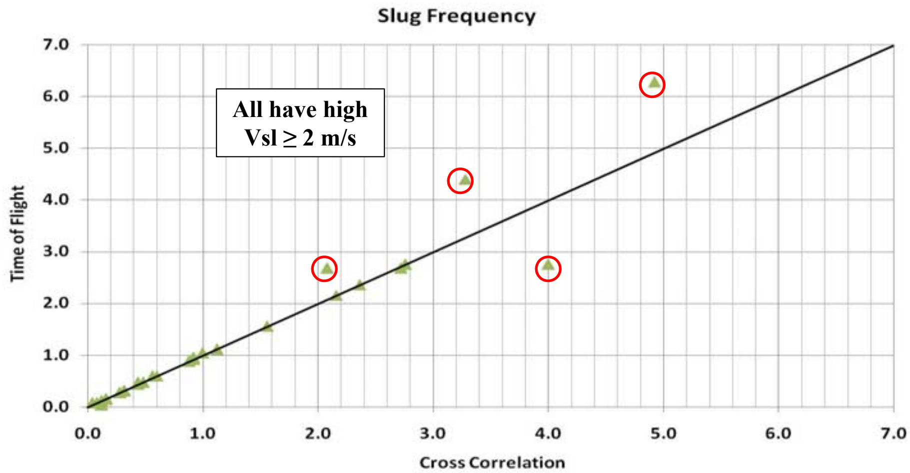
Translation Velocity

- Cross Correlation
- Time of Flight
  - Detect Start of Slug or Film at Each Capacitance Sensor
  - *t* is the Travel Time of a Slug Between Two Consecutive Sensors
  - *L* is the Distance Between Sensors
  - Translation Velocity = *L/t*

Cross Correlation vs. Time of Flight



Cross Correlation vs. Time of Flight …



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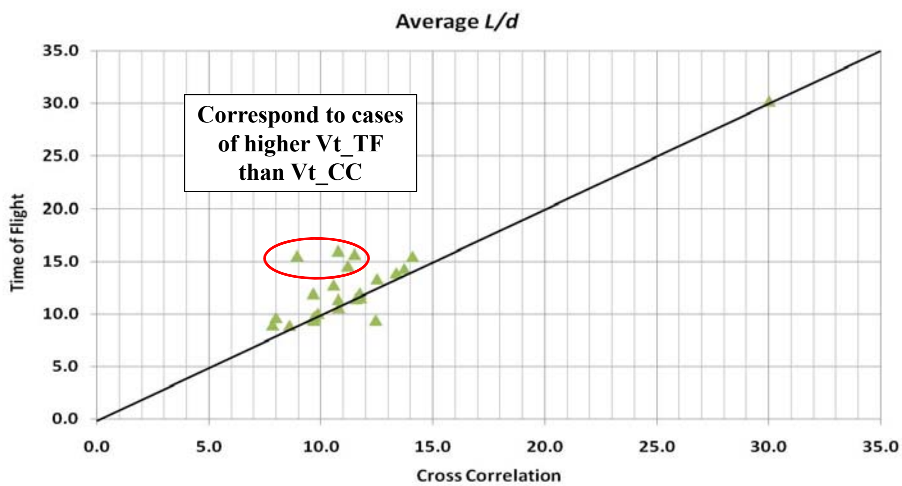
Cross Correlation vs. Time of Flight …



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Cross Correlation vs. Time of Flight …

	Advantages	Disadvantages
Cross Correlation	Does Not Require Signal Filtering	Estimates Only Overall Translation Velocity
Time of Flight	Will Estimate Front, Back and Average Translation Velocity	Uses Filtered Capacitance Signal
		May Require Additional Filtering If the Number of Slugs in the Two Capacitance Sensors is Different

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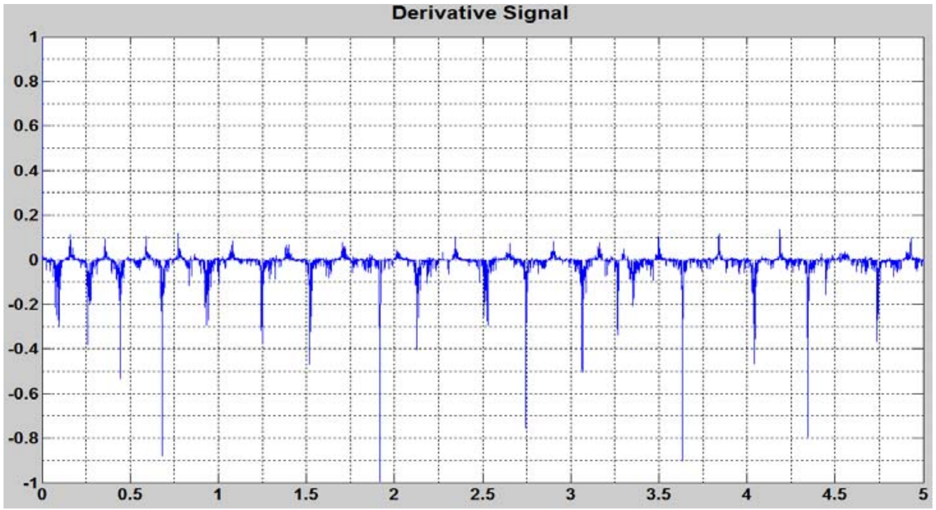
Region Identification With Derivative Method



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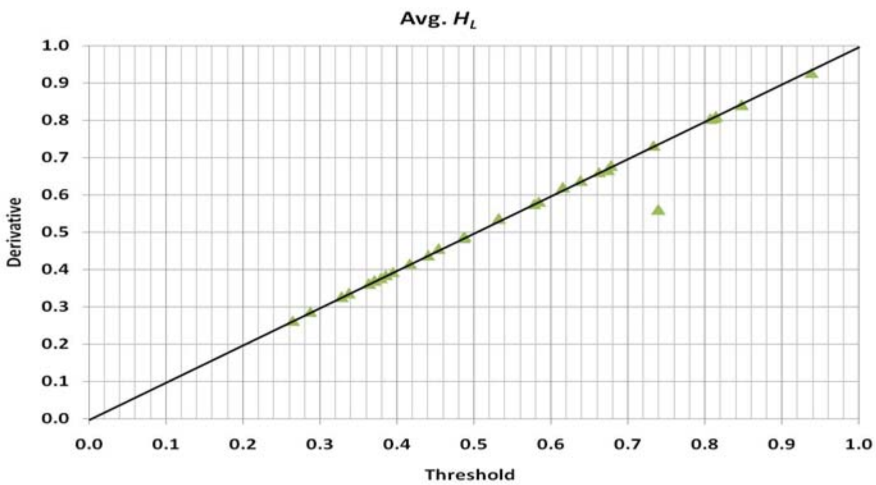
Average Liquid Holdup Derivative vs. Threshold



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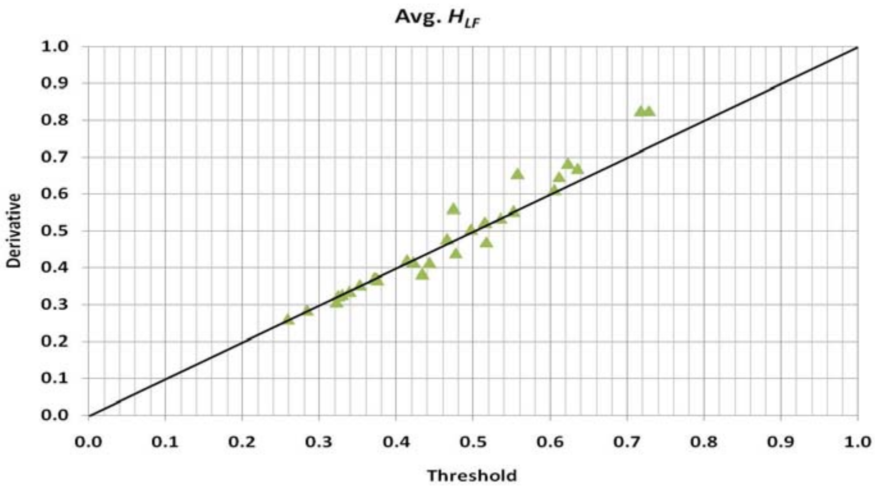
Film Liquid Holdup Derivative vs. Threshold



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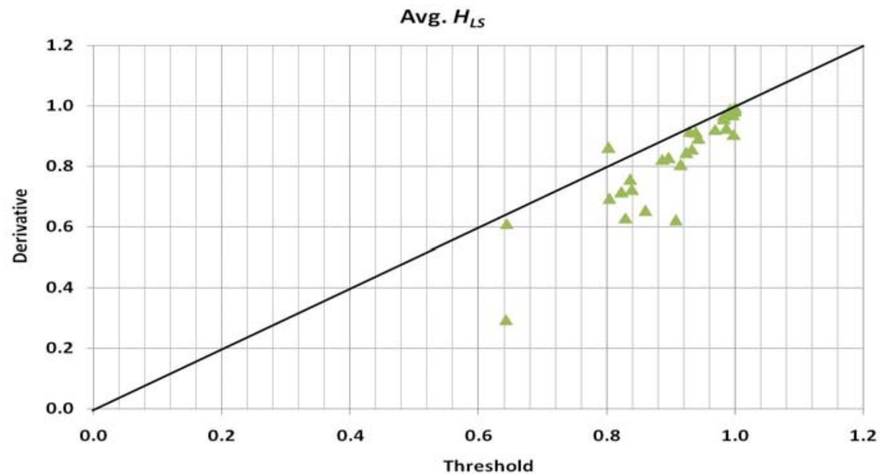
Slug Liquid Holdup
Derivative vs. Threshold



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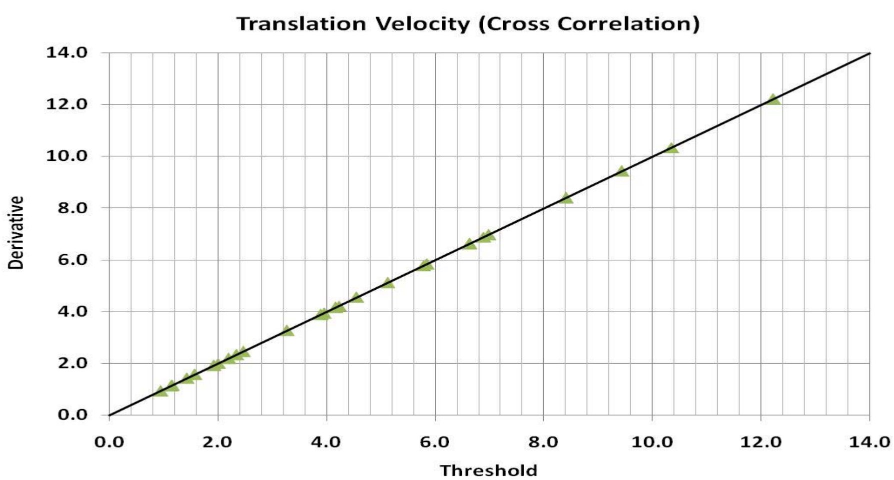
Translation Velocity
Derivative vs. Threshold (Cross Correlation)



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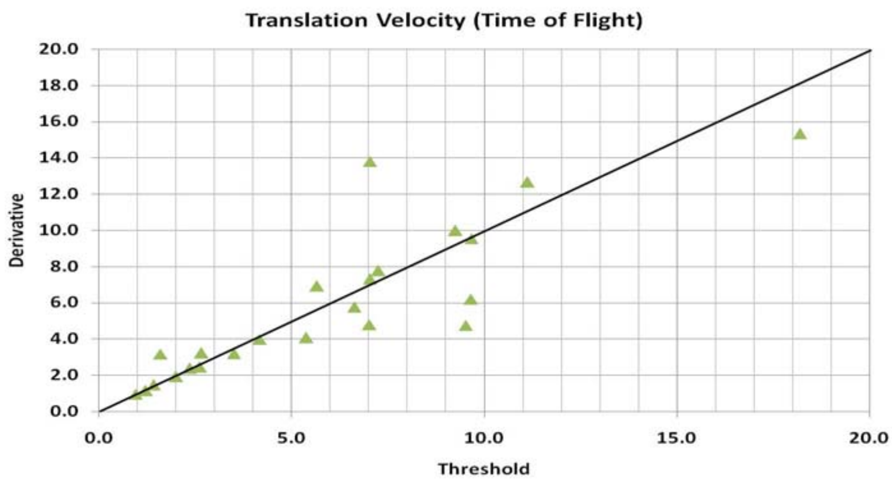
Translation Velocity
Derivative vs. Threshold (Time of Flight)



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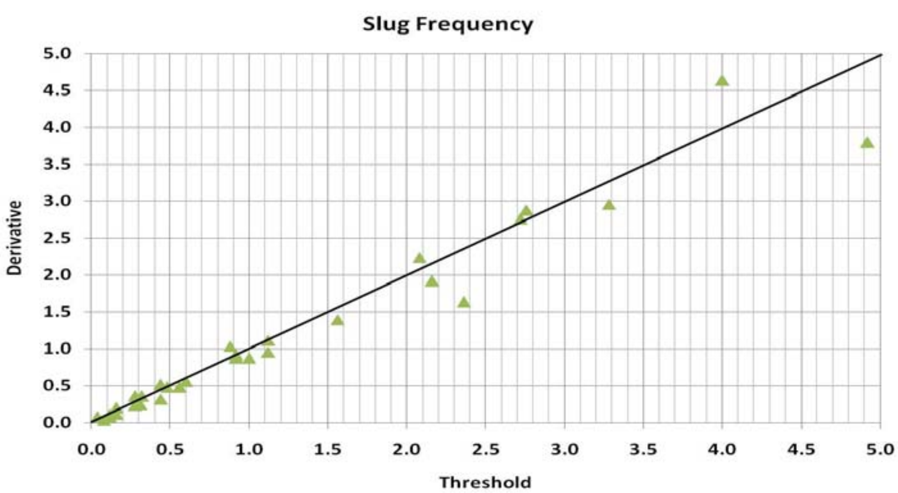
Slug Frequency
Derivative vs. Threshold



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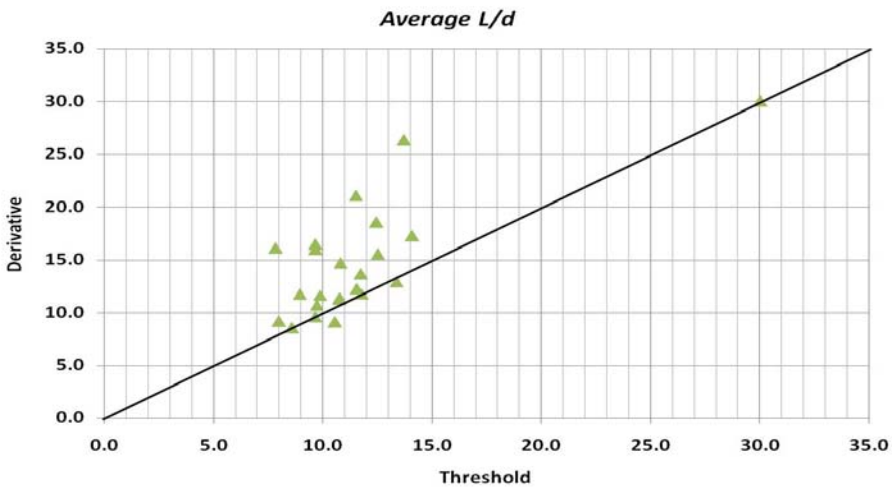
Average Slug Length Derivative vs. Threshold



Derivative vs. Threshold

	Advantages	Disadvantages
Threshold Method	Easy To Implement	Selecting Threshold Value is Subjective
Derivative Method	Visually can Indicate Start of Slug & Film Regions	Selecting Two Threshold Values

Period Accomplishments

- Facility
  - Modifications Completed
  - Operate Facility
- Calibrations Completed
  - DP-Angle, QCVs Speed, QCVS, Long QCV Section
- Writing Matlab Macros to Analyze the Acquired Raw Data Completed
  - Average & Uncertainty
  - Slug Characteristics

Future Activities

Completion Dates:

Literature Review	Ongoing
Sensor Calibration	Ongoing
Signal Processing Macros	Ongoing
Facility Modifications	Completed
Experimental Program	May 2014
Final Report	December 2014

Questions
&
Comments

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Pipes

Feras Alruhaimani

Project Completion Dates

Literature Review	Ongoing
Sensor Calibration	Ongoing
Signal Processing Macros	Ongoing
Facility Modification	Completed
Experimental Program	May 2014
Final Report	December 2014

Objective

The objective of this study is to conduct an experimental and modeling study on oil-gas two-phase flow using high oil viscosity (180 cP< μ_O< 587 cP) in vertical pipes. Acquired data will be used to verify and improve the closure relationships used for the existing mechanistic models.

Introduction

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

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

Other studies on high oil viscosity were conducted by TUHOP for two-phase gas-oil flow in vertical pipes (Akhiyarov, 2010) and three-phase gas-oil-water flow in horizontal and upward vertical pipes (Wang, 2012). In the experimental work of these studies, pressure drop and average liquid holdup were measured but no slug characteristics were acquired.

This study is part of the high oil viscosity efforts initiated by TUFFP, and is focused on the effect of high liquid viscosity on vertical gas liquid two-phase flow. In addition to pressure drop, flow pattern, and liquid holdup, slug characteristics are being studied.

Experimental Work

Experimental work is described in the sections experimental facility, test fluids and experimental program as follows:

Experimental Facility

The experimental work is being carried out in the TUFFP 2-in. ID three-phase flow facility. The facility consists of a closed-circuit loop with storage tanks, separator, progressive cavity pumps, heat exchangers, metering and test sections. The metering sections are equipped with Micro Motion™ Corriolis flow meters to measure mass flow rates and densities of the fluids, and with temperature transducers for monitoring temperatures. The test section is attached to an inclinable boom that can be raised to upward vertical position.

The new test section is designed as a 50.8-mm (2-in) ID 21.5-m (70.4-ft) long pipe consisting of a transparent polycarbonate pipe section to visually observe flow behavior. It is connected to a 21.5-m (70.4-ft) long, 50.8-mm (2-in.) ID return pipe which is set parallel to the test section at the same height. The instrumentations are mounted on the pipe section for detailed measurements of the flow characteristics.

Test Fluids

The fluids used in the experiments are mineral oil and compressed air. Lubsoil ND-50 is selected due to its high viscosity and Newtonian behavior in the testing range. The physical properties of the oil are given below:

- API gravity: 28.5°.
- Pour and flash point temperatures: -15° C (5° F) and 265° C (510° F), respectively.
- Surface tension: 35.75 dynes/cm at 19.8° C (68° F) and atmospheric pressure.
- Density: 884.4 kg/m^3 @ standard condition.

Experimental Program

The experiments will be conducted using air and oil in the vertical pipe. The oil viscosity will vary from 181 to 587 cP. The ranges of superficial liquid and gas velocities are 0.05 to 2 m/s and 0.5 to 3 m/s, respectively.

Experiments will be conducted to acquire data on flow pattern, measure pressure drop, liquid holdup, and slug characteristics. The experimental results will be used to validate the performance of existing models. New closure relationships will be developed as needed.

Instrumentation

The test section is equipped with four differential pressure transducers for pressure gradient measurements. Additionally, five quick-closing valves are installed for holdup measurements and bypassing. Two of these quick-closing valves are utilized to capture either the slug body or bubble region. Slug characteristics are obtained from the two wire-type capacitance sensors. Moreover, a high-speed video camera and surveillance cameras will be used to observe the slug flow development and monitor the oil and air mixing status.

Capacitance Sensor

Seven capacitance sensors will be installed in the test section, two at the entrance, two in the middle, two toward the end, and one at the end of the test section. The data acquired from the capacitance sensors will be used to analyze the evolution of the slug characteristics as well as the average liquid holdup.

The capacitance sensors must be properly calibrated. Static calibrations have been conducted on ten capacitance sensors to determine best sensors to be used in the test section. Best sensors are the ones that the signals are stable and repeatable. Dynamic calibration will also be performed on the capacitance sensors to obtain a relation between the voltage signal and liquid holdup for each sensor.

Data Gathering and Processing

Three different data streams, low speed, high speed, and video recordings will be collected. Low-speed data include pressure, pressure gradient, temperature, mass flow rates, densities, viscosities, and superficial velocities. High-speed data will be the voltage readings from the capacitance sensors.

Data management is a major challenge for this study due to the large amount of data to be acquired. Therefore, the data processing has to be automated. Two Matlab macros have been developed: the first one is to calculate the average and uncertainty of all the low-speed data, and the second one is for the determination of slug characteristic.

In case of slug flow, the high-speed Matlab macro will be used to calculate the slug characteristics: translation velocity, average slug length, slug length distribution, slug frequency, slug liquid holdup, film liquid holdup, and average liquid holdup.

In addition to using the threshold method to identify the slug region, a new derivative method is also utilized in Matlab macros. The derivative method is based on plotting the capacitance sensor derivative voltage versus time, a positive peak in signal will indicate the start of slug and a negative peak in signal will indicate the start of the film region.

In the Matlab macro, two methods for estimating translation velocity between two adjacent capacitance sensors were used. The first method is cross-correlation where a Matlab function is used to estimate the maximum delay in the signal between two capacitance sensors. The second method is the time of flight method. This method uses the passage time of slug (film) between the two consecutive sensors.

The Matlab macro has been tested with data from Brito (2012) for verification. The results obtained by Matlab were consistent with the results obtained by Brito.

Near Future Work

- Dynamic calibration of capacitance sensors.
- Start experimental work.

References

Gokcal, B.: "Effect of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes," MS Thesis, The University of Tulsa, Tulsa, OK, 2005.

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Brito, R.: "Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes," MS Thesis, The University of Tulsa, Tulsa, OK, 2012.

Akhiyarov, D.: "High-Viscosity Oil/Gas Flow in Vertical Pipe," MS Thesis, The University of Tulsa, Tulsa, OK, 2010.

Wang, S.: "High-Viscosity Oil/Water/Gas Flow in Horizontal and Upward Vertical Pipes: Slug Liquid Holdup Modeling," Ph.D. Dissertation, The University of Tulsa, Tulsa, OK. (2012).

Al-Safran, E.: “An Experimental and Theoretical Investigation of Slug Flow Characteristics in the Valley of a Hilly-Terrain Pipeline”, PhD Dissertation, The University of Tulsa, Tulsa, OK, 2003.

Fluid Flow Projects

Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Downward Pipes

Sunghoon Chung

Advisory Board Meeting, September 25, 2013

Outline

- Objectives
- Introduction
- Literature Review
- Experimental Study
  - 3-Phase TUFFP Facility
  - Test Fluid
  - Experimental Program
- Data Acquisition
- Future Activities

Objectives

- Perform Experimental and Modeling Study for Two-Phase Downward Flow in Vertical Pipes for High-Viscosity Oils (180 cP< μ_O< 587 cP)
- Closure Relationship Modification to Improve Performance of Existing Mechanistic Models as Necessary

Introduction

- Few Investigations in Two-Phase Vertical Downward Flow with Air-Water Condition
- Demand of Accurate Prediction with the Growth of Deep-Water Production
- TUFFP Experimental Studies Revealed That Existing Two Phase Flow Mechanistic Models Perform Poorly for High Oil Viscosities (μ_O >180 cP)

Fluid Flow Projects Advisory Board Meeting, September 25, 2013

Literature Review

- Barnea *et al*. (1982) and Usui (1989)
  - Test Fluid : Air-Water
  - Transition Criteria of Flow Patterns Based on Theoretical Models
    - Annular - Slug
    - Slug - Dispersed Bubble
    - Slug – Falling Film (Usui)
    - Occurrence of Liquid Droplet (Usui)

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Literature Review …

- Bhagwat and Ghajar (2012)
  - Direct Comparison between Upward and Downward Flow (Flow Patterns, Void Fraction)
  - Tested the Performance of 52 and 26 Different Void Fraction Correlations for Upward and Downward Vertical Flow
  - Proposed Top Five Performing Correlations

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Literature Review …

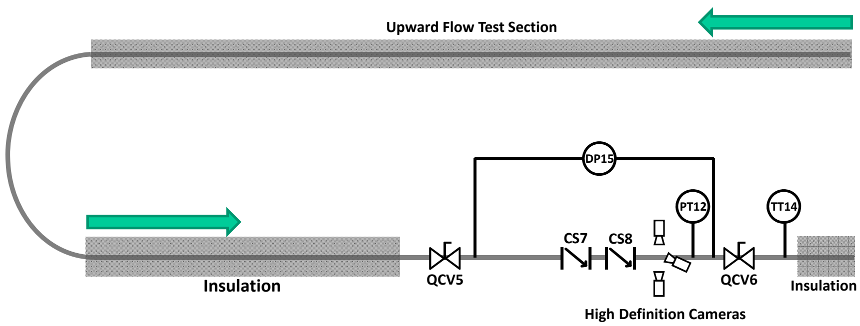
- Julia *et al.* (2013)
  - Test Fluid: Air-Water
  - Identified Local and Global Flow Patterns Using Distribution of Bubble Chord Length with Self-Organized Neural Network
  - Compared Global Flow Pattern Identification Results with Usui's Theoretical Model (1989)

Three-Phase Flow Facility

Return Line for the 2" Gas-Oil-Water Facility

Three-Phase Flow Facility …

- Test Section



Fluid Flow Projects

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Test Fluids

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

Fluid Flow Projects

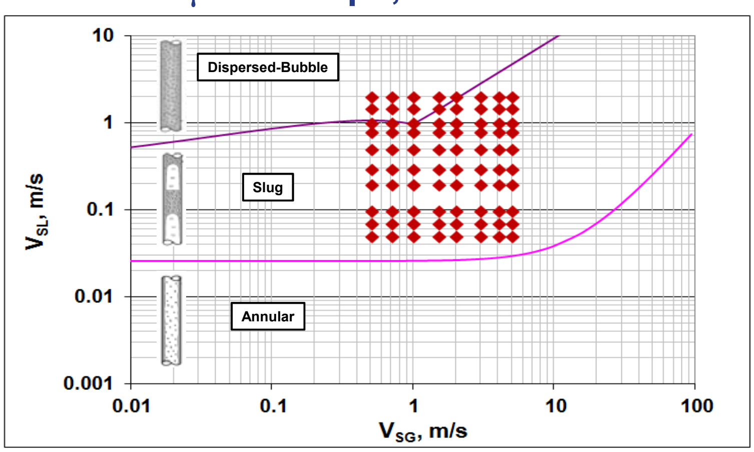
Advisory Board Meeting, September 25, 2013

Experimental Program

- Viscosity
  - 181 – 587 cP
- Inclination
  - Vertical
- Superficial Liquid Velocity
  - 0.1 – 3 m/s
- Superficial Gas Velocity
  - 0.1 – 5 m/s

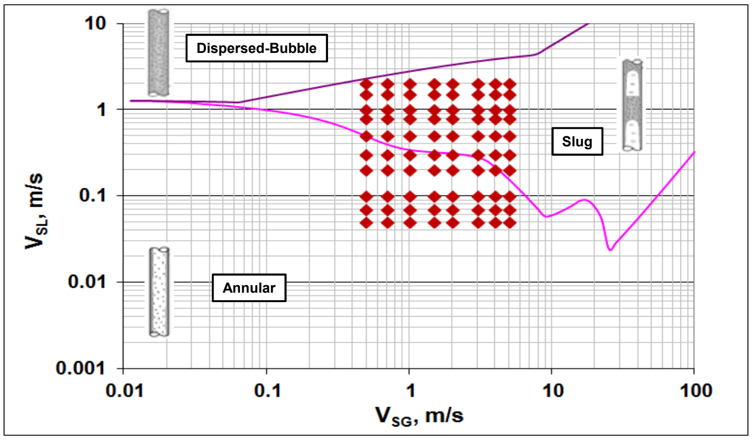
Flow Pattern (Barnea)

μ = 378 cp , θ = -90°



Flow Pattern (Unified)

μ = 378 cp , θ = -90°



Data Acquisition

- Two-Phase Flow Parameters
  - Flow Pattern
  - Pressure Drop
  - Liquid Holdup
  - Slug Characteristics
    - Slug Length
    - Slug Frequency
    - Translational Velocity

Future Activities

Completion Dates

- Literature Review — Ongoing
- Signal Processing Macros — Ongoing
- Dynamic Experiments — Ongoing
- Experimental Program (start) — October 2013
- Final Report — March 2015

Questions
&
Comments

Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Downward Pipes

Sunghoon Chung

Project Completion Dates

Literature Review	Ongoing
Static Experiments	Complete
Signal Processing Macros	Ongoing
Dynamic Experiments	Ongoing
Experimental Program	October 2013
Final Report	March 2015

Objectives

The main objective of this project is to perform an experimental and modeling study for two-phase downward flow in vertical pipes with high viscosity oil (180 cP< μ_O< 587 cP). The closure relationships will be suggested for improving the performance of existing mechanistic models as needed.

Introduction

A large number of experimental and modeling studies on gas-liquid two-phase flow have been carried out owing to its importance in industrial applications. Most of the studies have been focused on horizontal and vertical upward flow. Only a few investigations in vertical downward two-phase flow have been reported (Barnea *et al.*, 1982; Usui, 1989; Bhagwat and Ghajar, 2012; Julia *et al.*, 2013) due to the relatively short length of pipes encountered in traditional offshore production operations. With the growth of deep-water production, however, vertical down-comers from platforms to the seafloor may have lengths of several thousand feet. Accordingly, more accurate prediction of pressure drop and liquid holdup over these lengths becomes very important.

Aforementioned studies on vertical downward flow correspond to air-water two-phase conditions. As can be seen in previous studies by TUFFP (Gokcal, 2005; Kora, 2010), however, existing mechanistic models show poor performance for two- phase flow with high viscosity liquid. Analogically, we can expect mechanistic models of vertical downward two-phase flow also present poor prediction in high liquid viscosity conditions.

This research project will be performed in conjunction with the "Effect of high oil viscosity on oil-gas flow behavior in vertical flow" project. Data will be measured simultaneously from separate data acquisition systems, sharing an experimental facility, test fluids and flow conditions. The successful completion of these projects can provide better understanding about vertical two-phase flows with high viscosity liquid.

Experimental Study

Experimental Facility Design

The experimental work will be conducted using the TUFFP 2-in. ID three-phase flow facility located at the University of Tulsa North Campus Research Complex. It consists of a closed circuit loop with storage tanks, a separator, progressive cavity pumps, heat exchangers, and metering and test sections for upward and downward flow. The metering sections are equipped with Micro Motion™ Corriolis flow meters to measure mass flow rates and densities of the fluids and with temperature transducers for monitoring temperatures. The test section is attached to an inclinable boom that can be raised to an upward vertical position.

The test section for downward flow is in a 21.1-m (69.3-ft) long, 50.8-mm (2-in.) ID return pipe section. Transparent polycarbonate pipe of 3.59 m (11.8 ft) long is placed at the middle of the return pipe section to observe flow behavior. The instrumentations, including capacitance sensors, pressure transducers, and quick closing valves are mounted on the pipe section for detailed measurements of the flow characteristics. Finally, high-speed cameras are installed to observe flow behavior in the vertical position.

Test Fluids

The fluids used in the experiments are mineral oil and compressed air. Lubsoil ND-50 is selected due to its high viscosity and Newtonian behavior in the testing range. The detailed property of this oil will be tested in the laboratory. The physical properties of the oil are given below:

- API gravity: 28.5°.
- Density: 884.4 kg/m^3 @ standard condition.
- Pour and flash point temperatures: -15° C (5° F) and 265° C (510° F), respectively.
- Surface tension: 35.75 dynes/cm at 19.8° C (68° F) and atmospheric pressure.

Experimental Program

The oil viscosity will vary from 181 to 587 cP, by changing the temperature of the fluid. The ranges of superficial liquid and gas velocities are 0.05 to 2 m/s and 0.5 to 3 m/s, respectively.

Experiments will be conducted to acquire flow pattern, and to measure pressure drop, liquid holdup, and slug characteristics. The experimental results will be used to test the performance of existing models. New closure relationships will be developed if necessary.

Data Acquisition

Two-wire type capacitance sensor previously used by Kora (2010) and Brito (2012) was chosen due to the linear response and low sensitivity to temperature change.

Two capacitance sensors will be installed at the middle of the acrylic section. They will be used to analyze the evolution of the slug characteristics as well as the average liquid holdup. Performing static and dynamic calibrations is essential to convert properly measured voltage signals into liquid holdup value.

Static calibration is performed to obtain the relationship curve between dimensionless voltage and liquid holdup. The curves are deduced by measure liquid film thicknesses and corresponding voltages for each capacitance sensor. Static calibration for the capacitance sensors in downward flow section has been completed.

Data Processing

Data management is a major challenge for this study due to the large amount of data by automatic data acquisition system. A MATLAB macro will be used to make the data processing automated since it can handle a larger volume of data. Uncertainty of analysis will also be performed by MATLAB macro.

Near Future Work

- Finish modification of signal processing macro in MATLAB.
- Test oil in laboratory to obtain actual fluid property.
- Quick-closing valve system calibration.

Reference

Barnea, D., Shoham, O., and Taitel, Y.: “Flow Pattern Transition for Vertical Downward Two-phase Flow,” *Chemical Engineering Science*, 37(5), pp. 741-744, 1982.

Bhagwat, S. M., and Ghajar, A. J.: “Similarities and Differences in the Flow Patterns and Void Fraction in Vertical Upward and Downward Two-phase Flow,” *Experimental Thermal and Fluid Science*, 39, pp. 213-227, 2012.

Brito, R.: “Effect of Medium Oil Viscosity on Two-phase Oil-Gas Flow Behavior in Horizontal Pipes,” MS Thesis, The University of Tulsa, Tulsa, OK, 2012.

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Kora, C.: “Effect of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes,” MS Thesis, The University of Tulsa, Tulsa, OK, 2010.

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Fluid Flow Projects

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

Samet Ekinci

Advisory Board Meeting, September 25, 2013

Outline

- Objectives
- Literature Review
- Experimental Facility
- Experimental Program
  - Static Calibration
  - Dynamic Calibration
- Future Work

Objectives

- Experimental Analysis of Inclination Angle Effect (±2° From Horizontal) in High Oil Viscosity Two-Phase
- Validate Models/Correlation with Experimental Results

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Literature Review

- Effect of Liquid Viscosity on Two-Phase Flow Behavior
  - Colmenares *et al. (2001)*
    - μ_L = 480 cP
  - Gokcal *(2006)*
    - 181 cP ≤ μ_L ≤ 587 cP
  - Brito *(2012)*
    - 39 cP ≤ μ_L ≤ 166 cP

Fluid Flow Projects

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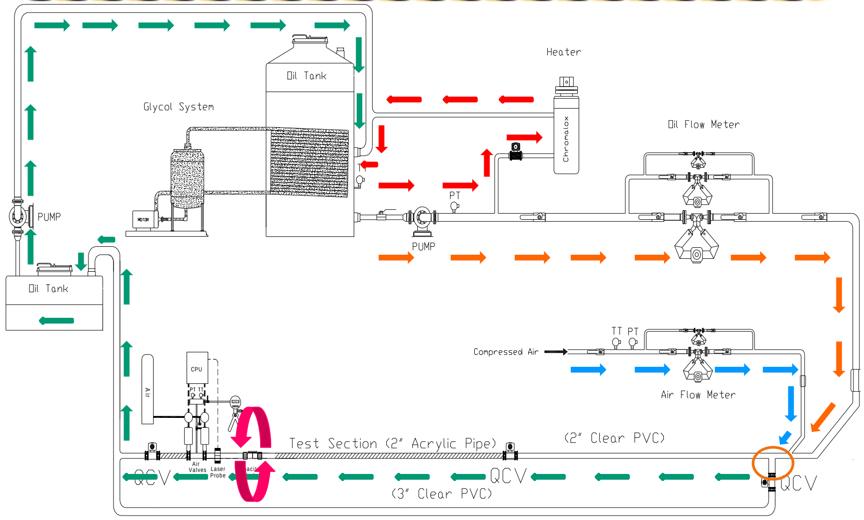
Literature Review …

- Effect of Liquid Viscosity on Slug Flow Characteristics
  - Nadler and Mewes *(1995)*
    - 1 cP ≤ μ_L ≤ 37 cP
  - Gokcal *et al. (2010)*
    - 181 cP ≤ μ_O ≤ 587 cP
- Effect of Liquid Viscosity on Slug Flow
  - Rosa *et al. (2004)*
    - 1 cP ≤ μ_L ≤ 27 cP

Literature Review …

- Effect of Inclination on Two-Phase Flow Characteristics
  - Jeyachandra *et al. (2011)*
    - 1 cP ≤ μ_L ≤ 585 cP

Experimental Facility



Fluid Flow Projects

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Experimental Facility …

Fluid Flow Projects

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Experimental Program

- Inclination
  - 2 Degrees Downward and Upward
- Superficial Liquid Velocity
  - 0.1 – 0.8 m/s
- Superficial Gas Velocity
  - 0.5 – 5 m/s
- Temperature
  - 80 – 110° F

Fluid Flow Projects

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Static Calibration

- Height of the Fluid, h_L, and the Voltage Output, V_{read}, is Measured Simultaneously
- Output Voltage Value is Converted to the Dimensionless Voltage, $\tilde{V}$

$$\tilde{V} = \frac{V_{read} - V_{\min}}{V_{\max} - V_{\min}} \quad \text{(Brito, 2012)}$$

- Liquid Holdup, H_{LST}, is Determined

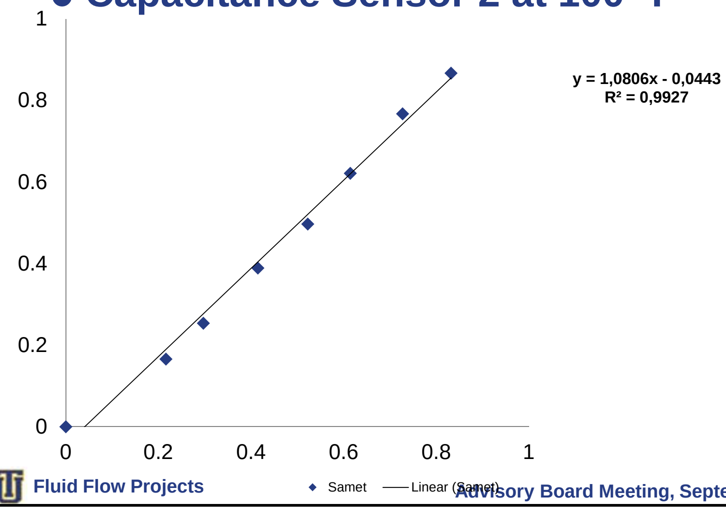
$$H_{LST} = \frac{\pi - \arccos(2h_L - 1) + (2h_L - 1)\sqrt{1 - (2h_L - 1)^2}}{\pi} \quad \text{(Shoham,2002)}$$

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Static Calibration …

Capacitance Sensor 2 at 100 °F



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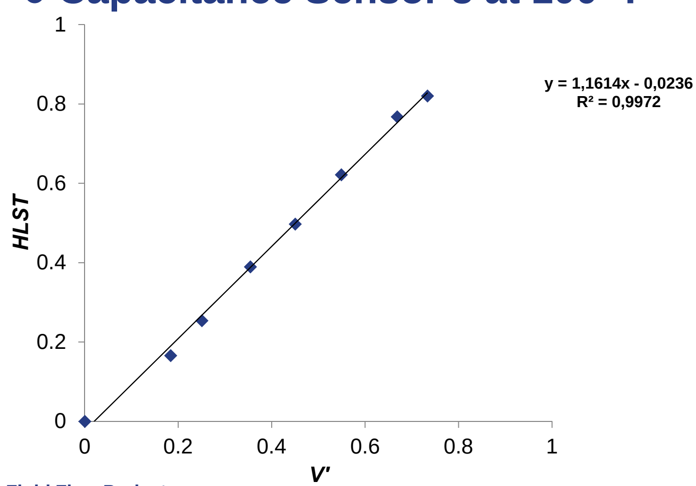
Static Calibration …

Capacitance Sensor 3 at 100 °F



Fluid Flow Projects

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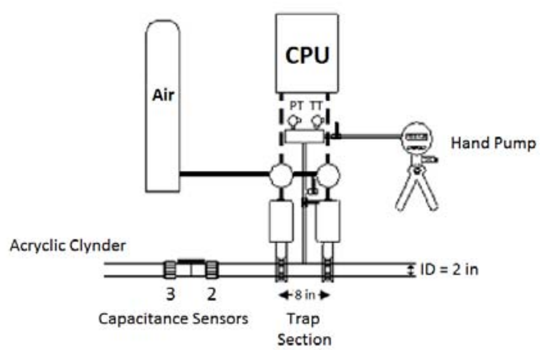
Dynamic Calibration

- Quick-Closing Valve System (QCVS)
- Slug body is Captured by QCVS
- Acrylic Cylinder Connected with Trapped Section
- Pressure from QCVS (Brito, 2012)

$$H_{L(QCV)} = \frac{V_{TrapSection}}{V_{Oil}}\left(-19945p^2 + 133.48p - 1763.1\right)$$

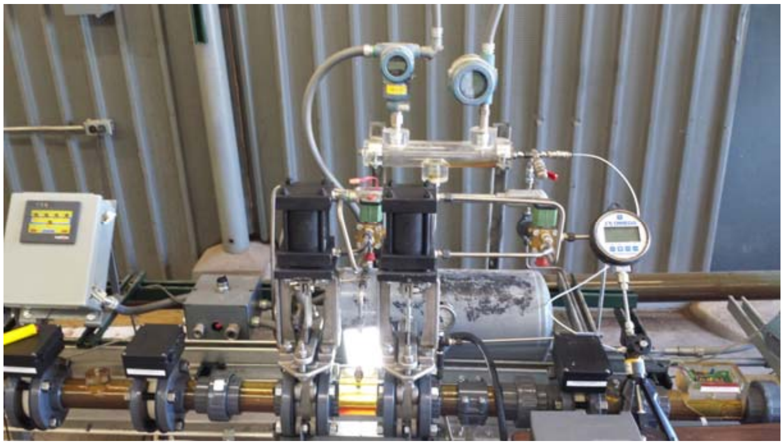
- Static Calibration (H_{LST}) vs. Dynamic Calibration ($H_{L(QCV)}$)

Dynamic Calibration …



Schematic of Quick-Closing Valve System

Dynamic Calibration …



Schedule

Literature Review	Ongoing
Static Calibration	Completed
Dynamic Calibration	Oct 2013
Data Collection	Oct 2013- Feb 2014
Model Comparison	Feb - Mar 2014

THANKS …

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

QUESTIONS

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

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

Samet Ekinci

Project Completion Dates

Literature Review .... Ongoing
Static Calibration .... Completed
Dynamic Calibration .... October 2013
Data Collection .... October 2013 -February 2014
Modeling Comparison .... February - March 2014

Objectives

The main objectives of this project are twofold:

1. Experimental analysis of inclination angle effect (±2° from horizontal) on high viscosity oil and gas two-phase flow.
2. Validate the available models/correlations using experimental results.

Introduction

Highly viscous oil and gas two-phase flow production is often observed in the oil industry. Highly viscous oils exhibit different flow behavior during production in comparison to low viscosity oils. Most models and correlations have been developed for low viscosity oils. Thus, understanding gas-liquid two-phase flow behavior in pipes is needed for highly viscous oils.

TUFFP has initiated an effort to increase the understanding of high viscosity oil two-phase flow behavior. Gokcal (2005) carried out an experimental program to understand the oil viscosity effects on flow pattern, pressure drop and liquid holdup. Considerably different flow behavior was observed which cannot be predicted by the available models. Later, Gokcal (2008) analyzed the viscosity effect on slug flow characteristics, namely, slug length, frequency and translational velocity. Soon after, Kora (2010) conducted an experimental program to measure the slug liquid holdup using a two-wire capacitance sensor. Recently, Brito (2012) upgraded the facility instrumentation by adding four capacitance sensors stations along the developing region. Additionally, high-definition cameras have been installed and synchronized along the flow loop, facilitating the observation of flow development.

A study for inclination angle effects (±2° from horizontal) was conducted by Jeyachandra (2011). Further performance analysis of the used capacitance sensors indicated that some of the holdup data of Jeyachandra needed to berepeated . The experiments will be performed for the inclination angle of -2° and +2°. Gas and oil flow rates will be 0.5 - 5.0 m/s and 0.1 - 0.8 m/s, respectively. This effort will not only improve the accuracy of collected data but will also provide information about slug evolution, allowing further analysis of the inclination effects.

Experimental Study

The indoor high viscosity oil-gas facility is modified to perform experiments to study inclination effects. The capacity of the oil storage tank is 3.03 m^3. A 20-hp screw pump is used to push the liquid through the loop. Air is delivered through a dry rotary screw-type compressor. The oil and the air are mixed at a tee junction before proceeding to the test section.

The facility is comprised of a metering section, a test section, a heating system and a cooling system. The test section is 18.9 m (62 ft) long, 50.8-mm (2-in.) ID pipe. Nearly half of the pipe is made of clear PVC pipe, and the rest is made of transparent acrylic pipe.

A 9.15-m (30 ft) long transparent acrylic pipe section is used to observe the flow behavior visually. A flexible hose connects the test section with the 76.2 mm (3-in.) ID return pipe. An oil transfer tank (1.32 m^3) is located at the end of the return pipe. The return pipe is connected to this tank with a flexible hose. A 3-hp progressing cavity pump is used to pump the oil from the new tank back to the main tank through the riser. The oil flow rates are measured at the inlet of the facility using MicroMotion mass flow meters (CMF025, CMF100, and CMF300). The air is measured at the inlet of the facility using MicroMotion mass flow meters (CMF025 and CMF050).

Separation is accomplished by gravity segregation of air and oil. The separated air is removed through the ventilation system. The test section is supported on stands and the inclination of the test section can be set from -2° to 2° from horizontal by adjusting the heights of the stands.

The viscosity of the oil is controlled by controlling the temperature of oil at the tank. A 20-KW Chromalox heater capable of heating the heavy oil from 70°F to 140°F is used. The heating and the cooling sections thus play a major part in the experiment to control the viscosities. Resistance Temperature Detector (RTD) transducers measure the temperatures during experiments. Pressure transducers and differential pressure transducers are located at different places to measure pressure and pressure drop in the loop.

Test Fluids

The gas phase is compressed air and the high viscosity oil for this study is CITGO Sentry 220. Following are the typical properties of the oil:

- Gravity: 27.6° API
- Viscosity: 0.220 Pa·s @ 40° C
- Density: 889 kg/m^3@ 15.6° C
- Surface tension: 0.03 N/m @ 40° C

Instrumentation and Measurement

This section presents the measured variables and the instrumentation considered in this study.

Flow Patterns

Flow patterns are observed from a rectangular prism-shaped visualization box made of acrylic. The test section runs through the box. The space between the pipe and box is filled with glycerin. The TUFFP high-speed camera is positioned in front of the box during high-speed video captures.

Differential Pressure (DP)

There are four differential pressure transducers on the flow loop. DP1 and DP2 are located at the PVC section of the loop and are used for monitoring the development of flow. DP3 and DP4 are located at the acrylic section and are used for measuring the differential pressure.

Average Liquid Holdup

A set of quick closing valves (QCVs) will be used for average liquid holdup measurement. Due to the pipe inclination, the amount of liquid trapped between the QCV can be correlated with the liquid level. Thus, no drainage is necessary in the average holdup measurement.

Slug Characteristics

The acrylic section has three stations of two-wire capacitance sensors (CS). Each station is comprised of two consecutive capacitance sensors allowing the estimation of translational velocity, slug frequency and slug length. Brito's (2012) signal processing macros will be used to determine slug characteristics.

Slug Liquid Holdup

The most challenging part of this study is measuring holdup in liquid slugs. CSs will be used for the measurement of slug liquid holdup.

Two-wire CSs are used in this study. These sensors consist of two parallel copper wires positioned perpendicular to the flow at a distance of 0.25 in. These sensors require an electronic circuit to filter, amplify and convert the measured capacitance to a voltage. The MS3110 Universal Capacitive Readout IC has been utilized to convert the capacitance of the mixture to a 0 to 5 volt signal. It is equipped with a low pass filter providing an ultra-low noise and high-resolution capacitive readout.

Static Calibration

Static calibration of CS was accomplished by placing different amounts of liquid volumes in an acrylic pipe tester with the CS in the middle and measuring the height of the fluid in the pipe, then recording the corresponding sensor output voltage. The actual voltage reading was then converted to a dimensionless voltage. The corresponding liquid holdup was calculated as the ratio of the volume of the liquid injected to the total volume of the tester. A graph of dimensionless voltage vs. liquid holdup was plotted and the resulting curve is the static calibration curve.

The shape of the static calibration curve is a straight line. This is expected because the two-wire capacitance sensor has two parallel copper wires positioned perpendicular to the flow direction.

Dynamic Calibration

Dynamic calibration of CSs will be conducted using the existing quick-closing valve system (QCV). The CS, QCV and high-speed video camera should be synchronized. The CS is placed 1.5 ft before the quick-closing valve system. Shortly before capturing the slug body with the QCV, the data collection process with CS will be started. The high-speed video camera is used to verify the trapped part of the slug body for the analysis of the CS reading. The dynamic calibration plot should be generated by plotting the actual liquid holdup data (QCV measurement) versus the calculated liquid holdup data (capacitance sensor output) at different test conditions. Finally, in order to calculate the liquid holdup in the slug body, numerical integration is used to estimate the area under the curve, and it is divided by the area as if the liquid slug is pure oil.

Data Processing

An Excel macro was developed by Brito (2012) to process the raw data and verify its quality through an uncertainty analysis. This Excel macro program calculates the average, standard deviation and uncertainty of all the measured and estimated parameters. The considered parameters are pressure gradient, absolute pressure, liquid temperature, mass flow rate, fluid properties (density and viscosity), superficial velocities, mixture velocity, mixture Reynolds number, and average liquid holdup. In addition, if slug flow is observed, additional parameters are calculated, namely, average liquid holdup in the film region, average liquid holdup in the slug region, number of slugs, slug frequency, translational velocity, slug length and slug length distribution.

Future Work

The static calibration has already been completed. Dynamic calibration will be completed by October 2013. Literature review and data collection will be completed by the beginning of 2014. Data analysis and modeling comparison will be finished soon after.

References

Gokcal, B.: "Effects of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes," MS Thesis, the University of Tulsa, Tulsa, OK, 2005.

Jeyachandra, B.: "Effect of Pipe Inclination on Flow Charcteristics of High Viscosity Oil-Gas Two-Phase Flow" MS Thesis, the University of Tulsa, Tulsa, OK, 2011.

Kora, C.: "Effect of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes," MS Thesis, the University of Tulsa, Tulsa, OK, 2010.

Brito, R.: "Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes" MS Thesis, the University of Tulsa, Tulsa, OK, 2012.

Fluid Flow Projects

Pipe Diameter Effect on Flow Characteristics for Medium and High Viscosity Oil-Gas Two-Phase Horizontal Flow

Taewoo Kim

Outline

- Objectives
- Introduction
- Literature Review
- Experimental Facility
  - Instrumentation
- Experimental Matrix
- Schedule

Objectives

- Acquire Experimental Data on Flow Characteristics for Medium and High Viscosity Oil-Gas Two-Phase Flow in 3-in Horizontal Pipes
- Compare the Results with 2-in ID Results Obtained from Previous Studies
- Validate Models/Correlation with Experimental Results

Fluid Flow Projects Advisory Board Meeting, September 25, 2013

Introduction

- Multiphase Flows May Exhibit Different Behavior as Pipe Diameter Increases
- There are Several Studies Addressing Diameter Effects on Low Viscosity Liquid and Gas Flows
- Previous High- and Medium-Viscosity Oil Two-Phase Studies are Mainly for 2-in ID pipes

Fluid Flow Projects Advisory Board Meeting, September 25, 2013

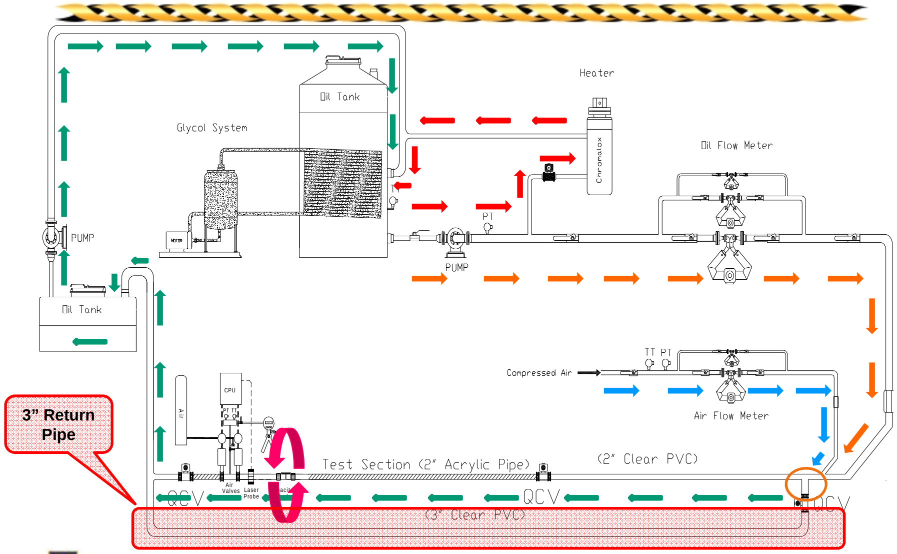
Literature Review

- Gokcal (2005)
  - Carried out Pioneering Experiments for High-Viscosity Oil Two-phase Flow in a 2-in ID Horizontal Pipe
  - Discovered Significantly Different Flow Behavior
  - Existing Models Performed Poorly
  - Diameter Effects were not Investigated
- Ben-Mansour *et al.* (2010)
  - Effect of Pipe Diameter and High Oil Viscosity on Drift Velocity
  - 3-in and 6-in ID Static Drift Velocity Data
  - No Other Data were Presented

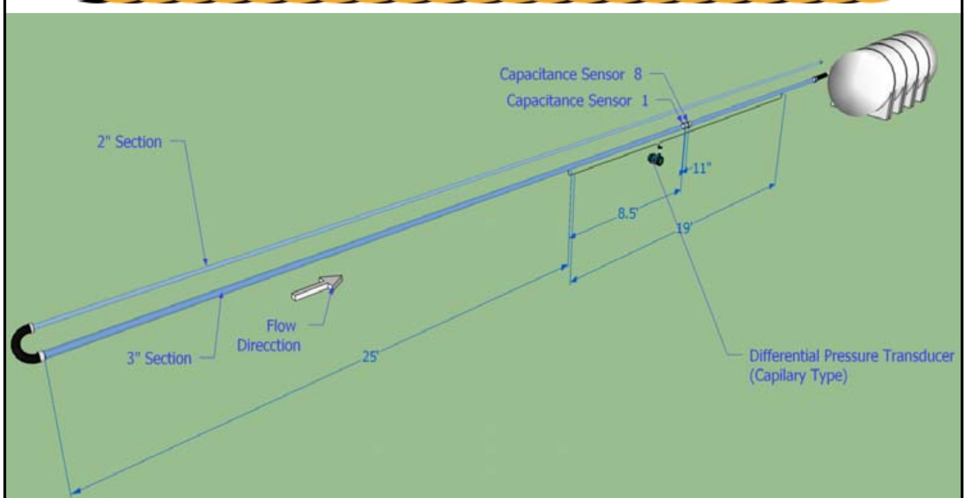
Literature Review …

- Brito (2012)
  - Carried Out Experiments for Horizontal Configuration Using Medium Viscosity Oil
  - Diameter Effect was not Considered

Experimental Facility



Experimental Facility



Measured Parameters

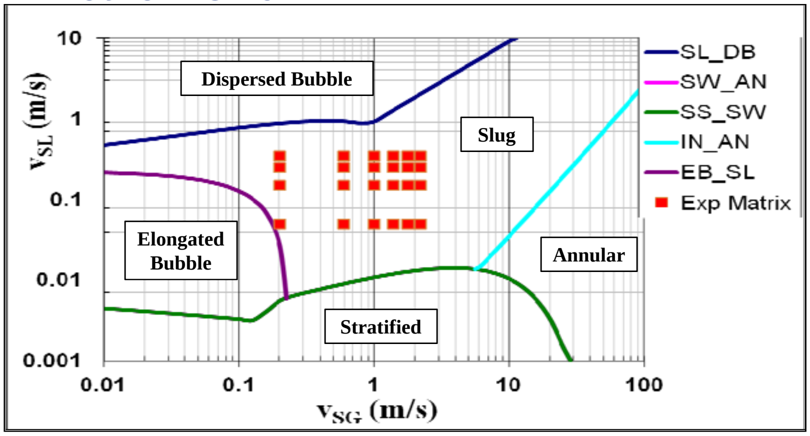
- High-Speed and High-Definition Camera
  - Flow Patterns
- Differential Pressure Transducer
  - Pressure Gradient
- Capacitance Sensors
  - Translational Velocity
  - Slug Frequency
  - Slug Length
  - Slug Length Distribution

Experimental Matrix

- Superficial Liquid Velocity
  - 0.05 – 0.35 m/s
- Superficial Gas Velocity
  - 0.05 – 2.0 m/s
- Temperatures
  - 80 – 110 °F (181 to 587 cP)
- Inclination
  - Horizontal (0°)

Flow Pattern Maps and Experimental Matrix

- Plot for 181 cP



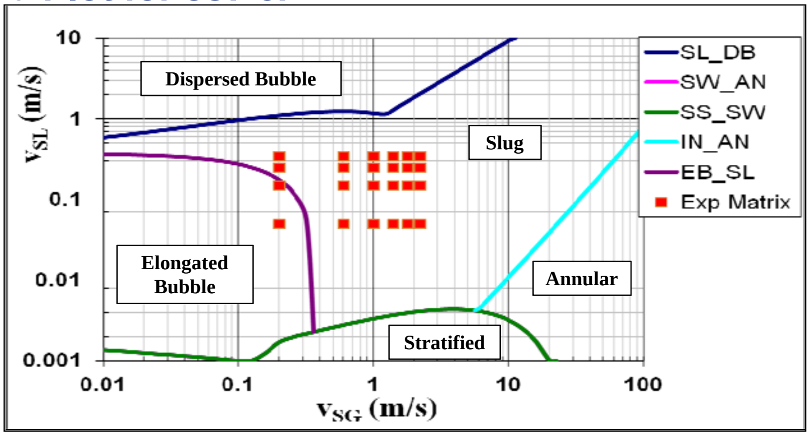
Barnea Model

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Flow Pattern Maps and Experimental Matrix

- Plot for 587 cP



Barnea Model

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Schedule

- Data Collection — Dec. 2013
- Data Analysis — Dec. 2013
- Model Comparison — Feb. 2014
- Report — June 2014

Thanks …

Questions

Pipe Diameter Effect on Flow Characteristics for Medium and High Viscosity Oil-Gas Two-Phase Horizontal Flow

Teawoo Kim

Project Completion Dates

Static Calibration	Oct 2013
Data Collection	Dec 2013
Data Analysis	Dec 2013
Modeling Comparison	Feb 2014
Report	Jun 2014

Objectives

The main objectives of this project are to experimentally investigate the pipe diameter effects on highly viscous two-phase flow in horizontal pipe and evaluate the performance of the existing models. A new set of experiments will be carried out in a 3-in pipe and results will be compared with Gokcal (2005) and Brito (2012) experimental observations.

Introduction

Oil-gas two-phase flow in pipes is a common occurrence in the petroleum, chemical, nuclear, and geothermal industries. In the petroleum industry, it is encountered in the production and transportation of oil and gas (Gokcal, 2005). Geometrical behavior of two-phase flow is called 'Flow pattern', and this depends on the flow rate of gas and liquid, diameter of the pipe, inclination angle of the pipe, and properties of fluid such as viscosities, densities of gas and liquid and surface tension.

Gokcal (2005) carried out an experimental program to analyze two-phase flow behavior for highly viscous liquids in a 50.8-mm (2-in) ID horizontal pipe. The author reported considerable changes on flow pattern, pressure drop, liquid holdup and slug characteristics as the liquid viscosity increases.

Recently, Brito (2012) completed an experimental study to analyze two-phase flow behavior for medium viscous oil in a 50.8-mm (2-in) ID horizontal pipe. The effect of viscosity on pressure gradient, liquid holdup and flow pattern was reported.

In this study, the 76.2-mm (3-in) ID return pipe of the 2" High Viscosity Oil/Gas Two-Phase Flow Loop will be used. The test section will be equipped with two capacitance sensor stations and differential pressure transducers. High speed and high definition cameras will be installed for flow observation. Flow pattern, pressure drop and slug characteristics such as translational velocity, slug length, slug frequency and film holdup will beobtained. The acquired data will be compared with the data presented by Gokcal (2005) and Brito (2012) using similar instrumentation and fluid properties (0.181 Pa·s and 0.587 Pa·s).

Experimental Study

Facility

The indoor high viscosity oil-gas facility is being modified to perform experiments to study the pipe diameter effect. The capacity of the oil storage tank is 3.03m^3. A 20 HP screw pump is used to push the liquid through the loop. Air is delivered through a dry rotary screw-type compressor. The oil and the air mix in a tee junction before proceeding to the 50.8-mm (2-in) ID pipe.

The facility is comprised of a metering section, a test section, a heating system and a cooling system. The test section is 13.4 m (44 ft) long, 76.2 mm (3-in) ID pipe.

A 10.22m (33-ft) long transparent PVC section is used to observe the flow behavior visually. A flexible hose connects the test section with the 50.8-mm (2-in) ID input pipe. An oil transfer tank (1.32 m^3) is located at the end of the test section, which is connected to this tank with a flexible hose. A 3-hp progressing cavity pump is used to pump the oil from the new tank back to the main tank through the riser. The oil flow rates are measured at the inlet of the facility using Micro Motion mass flow meters (CMF025, CMF100, and CMF300). The air is measured at the inlet of the facility using Micro Motion mass flow meters (CMF025 and CMF050).

Separation is accomplished by gravity separation of air and oil. The separated air is removed through the ventilation system.

The test section is supported on stands, and the inclination of the test section can be set horizontally by adjusting the heights of the stands.

The viscosity of the oil is controlled by controlling the temperature of oil at the tank. A 20 KW Chromalox heater capable of heating the heavy oil from 70° F to 140° F is used. The heating and the cooling section thus play a major part in the experiment to control the viscosities. Resistance

Temperature Detector (RTD) transducers measure the temperatures during experiments. Pressure transducers and differential pressure transducers are located at different points to measure pressure and pressure drop in the loop.

Test Fluids

The high viscosity oil to be used for this study is CITGO Sentry 220. The gas phase to be used is compressed air. Following are the typical properties of the oil:

- Gravity: 27.6° API
- Viscosity: 0.220 Pa·s @ 40° C
- Density: 889 kg/m^3 @ 15.6° C
- Surface tension: 0.03 N/m @ 40° C

Instrumentation and Measurement

Flow Patterns

The TUFFP high-speed video system will be used to identify the flow patterns.

Differential Pressure (DP) Measurement

One differential pressure transducer will be installed 25 ft from the inlet. The pressure ports will be 19 ft apart.

Slug Length, Slug Frequency, and Translational Velocity

The PVC section has provision for a pair of capacitance sensors. This will provide data for slug length, frequency and translational velocity.

Capacitance Sensor

The two-wire capacitance sensor is considered in this study. This sensor consists of two parallel copper wires positioned perpendicular to the flow at a distance of 0.25 in. This sensor requires an electronic circuit to filter, amplify and convert the measured capacitance to a voltage. The MS3110 Universal Capacitive Readout IC has been utilized to convert the capacitance of the mixture to a 0 to 5 volt signal. This chip is equipped with a low-pass filter providing an ultra-low noise and high-resolution capacitive readout.

Static Calibration

Static calibration of CS is accomplished by placing different amounts of liquid volumes in an acrylic pipe tester with the CS in the middle, and measuring the height of the fluid in the pipe, then recording the corresponding sensor output voltage. The actual voltage reading was then converted to a dimensionless voltage.

The corresponding liquid holdup was calculated as the ratio of the volume of the liquid injected and the total volume of the tester.

Data Processing

An excel macro was developed by Brito (2012) to process the raw data and verify its quality through an uncertainty analysis. This excel macro calculates the average standard deviation and uncertainty of all measured and estimated parameters. The considered parameters are pressure gradient, absolute pressure, liquid temperature, mass flow rate, fluid properties (density and viscosity), superficial velocities, mixture velocity, mixture Reynolds number and average liquid holdup. In addition, if slug flow is observed, additional parameters are calculated, namely, average liquid holdup in the film region, average liquid holdup in the slug region, number of slugs, slug frequency, translational velocity, slug length and slug length distribution. This macro will be adapted to this study.

Future Work

Sensor installation and static calibration will be finished by the end of September. Data collection will be carried out during fall (expected completion date is December 2013). Data analysis and modeling comparison will be finalized by February 2014. Final report will be delivered by June 2014.

References

Gokcal, B.: “Effects of High Oil Viscosity -on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes” M.S. Thesis, The University of Tulsa, Tulsa, OK (2005).

Gokcal, B.: “An Experimental and Theoretical Investigation of Slug Flow for High Oil Viscosity in Horizontal Pipes" Ph. D Thesis, The University of Tulsa, Tulsa, OK. (2008).

Brito, R. "Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes" Ms Thesis, The University of Tulsa, Tulsa, OK. (2012).

Fluid Flow Projects

Application of Minimum and Equal Energy Dissipation Concepts in Multiphase Flow Predictions

Al-Sarkhi, A.,
Pereyra, E., Sarica, C.

Advisory Board Meeting, September 25, 2013

Outline

- Objectives
- Introduction
- Modeling
- Prediction of Flow Pattern Transitions
- Conclusions
- Future Tasks

Objective

- **Develop Predictive Models for Multiphase Flow Behavior Using Minimum and Equal Energy Dissipation Concepts**

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Introduction

- **Theorem of Minimum Energy – *Chih and Charles (1986)***
  - ***"For a closed and dissipative system in a static stable equilibrium condition, its total energy is at its minimum value."***
- **Theorem of Minimum Rate of Energy Dissipation – *Chih and Charles (1986)***
  - ***"For a closed and dissipative system in a static stable equilibrium condition, its total rate of energy dissipation is at its minimum value."***

Fluid Flow Projects

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Advantages

- Force Balance or Momentum Conservation Approach is Complex and Involves Several Closure Relationships
- Energy Minimization or Minimum Energy Dissipation Approach is Simple, and Provides More Physics and Smooth Transitions Across Different Flow Patterns

Fluid Flow Projects
Advisory Board Meeting, September 25, 2013

Introduction

- Chakrabarti *et al.* (2005)
  - Developed a Liquid-Liquid Horizontal Flow Model for Stratified Flow Patterns Using Minimum Energy Concept and Combined Momentum Equation Together
  - Validated with Their Own Kerosene-Water Experimental Results and Lovick and Angeli (2004) Data

Fluid Flow Projects
Advisory Board Meeting, September 25, 2013

Introduction …

- Sharma *et al.* (2011)-TUFFP
  - Predicts Well All Flow Patterns Described in Trallero *et al.* (1997) as Well as Liquid Holdup And Pressure Gradient
  - Calculates Total Energy for All Flow Patterns Selecting the Flow Pattern Corresponding To the Minimum Energy
  - Combined Momentum Equation Also Was Satisfied

Introduction …

- Lee *et al.* (2013)-TUFFP
  - Demonstrated That the Minimum Dissipated Energy Corresponds to the Minimum Total Pressure Gradient
  - Modeled Stratified Flow Hydrodynamics in Horizontal Pipes Using the Minimum Energy Dissipated Concept
    - Liquid Level in Stratified Flow Calculated Without Use of Interfacial Friction Factor

Single-Phase Modeling

- Energy Dissipated in Single-Phase Flow

$$\Phi = \Delta P \times Q = \gamma \times Q \times h_L$$

- Head Loss, h_L, can Be Related to the Friction Factor, *f*, as

$$h_L = f \frac{L}{D} \frac{V^2}{2g}$$

- Friction Factor can Be Written as

$$f = C \, \mathrm{Re}^n$$

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Single-Phase Modeling …

- Laminar Flow
  - *n* = -1 and *C* = 64
- Turbulent Flow in Smooth Pipes
  - Blasius 1: *n* = -0.25 and *C* = 0.3164 (for *Re* Range from 3000 to 100,000)
  - Blasius 2: *n* = -0.2 and *C*= 0.184 Wide Range of the Reynolds Number
- Substituting in Φ

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Single-Phase Modeling …

- **The Rate of Energy Dissipation at the Transition Point must Be Equal**
  - **Blasius 1:**

$$\left.\begin{aligned}\Phi_L &= const.\times 64\,\mathrm{Re}^2 \\ \Phi_T &= const.\times 0.3164\,\mathrm{Re}^{2.75}\end{aligned}\right\} \mathrm{Re}_{cr}= 1187$$

  - **Blasius 2:**

$$\left.\begin{aligned}\Phi_L &= const.\times 64\,\mathrm{Re}^2 \\ \Phi_T &= const.\times 0.184\,\mathrm{Re}^{2.8}\end{aligned}\right\} \mathrm{Re}_{cr}= 1502$$

Single-Phase Modeling …

- **Remarks**
  - **Joseph (1976) Predicted the Critical Reynolds Number of 81 Using the Method of Energy Eigenvalue for Hagen-Poiseuille Flow**
  - **The Value of the Critical Reynolds Number of 1502 is Closer to the Value of 2000 Than Any Other Value Predicted by Other Methods in Literature**
  - **Nature Likes to Have a Laminar Flow**

Two-phase Modeling

- **Based on**
  - **Conservation Equations 1-D 2-Fluid Model (Lei (2013))→ (1)**
  - **Intermittent Flow Model Lei *et al.* (2013)→ (1)**

$$\Phi = v_m \times \left(\left. \frac{\Delta p}{L} \right|_f + (\rho_{TP} - \rho_h) g \sin\theta \right) A_p \qquad \textbf{(1)}$$

where

$$\rho_{TP} = \rho_L H_L + \rho_G (1 - H_L)$$
$$\rho_h = \rho_G \lambda_G + \rho_L (1 - \lambda_G)$$
$$v_m = v_{SL} + v_{SG}$$

$\left. \frac{\Delta p}{L} \right|_f$ →Frictional pressure drop

Two-phase Modeling (Procedure)

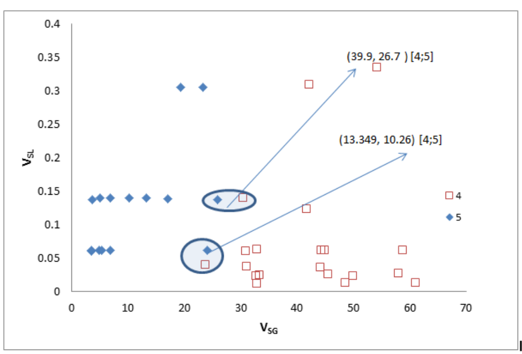
- **First Procedure**
  - **Calculate the Total Rate of Energy Dissipation for All Flow Patterns at the Same Operational Conditions**
  - **Select the Minimum Value as the Solution**
- **Second Procedure**
  - **Calculate the Total Rate of Energy Dissipation for All Flow Patterns**
  - **Search for the Locations Where the Rate of Energy Dissipations are Equal for Different Flow Patterns**
  - **This Will Provide the Flow Pattern Transitions**

First Procedure

- Was not Successful
  - Predicted Mostly Stratified for Horizontal Flow and Dispersed Bubble Flow in Vertical Flow
  - Due Partly to the Sensitivity to Models and Closure Relationships

Second Procedure (Equal Energy Dissipation Rate)

- Experimental Data of Andritsos (1986)

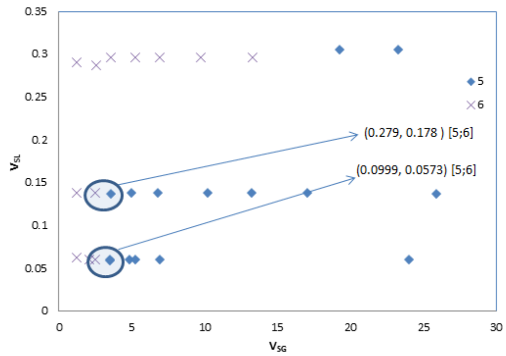


At the Transition Line: Energy Dissipation Rates are Almost the Same

Annular-slug Flow Transition for Air-Water Flow in a Horizontal 1-in. ID Pipe (4: Annular; 5: Slug)

Equal Energy Dissipation Rate

- **Experimental Data of Andritsos (1986) …**

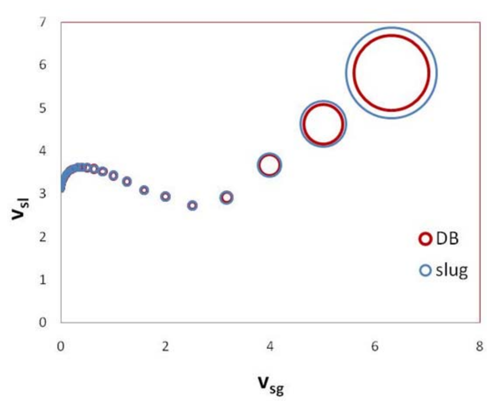


At the Transition Line: Energy Dissipation Rates are Almost the Same

Pseudo-Slug, Slug Flow Transition for Air-Water Flor in a Horizontal 1-in. ID Pipe (5: Slug; 6: Pseudo-Slug)

Model to Model Observation Along Transition Lines

- **Energy Dissipation Rate (Bubble Diameters) at the Slug-Dispersed Bubble Transition Line**
  - **Barnea Model**
  - **Air-Water Flow**
  - **0.0508-m ID Horizontal Pipe**



Energy Dissipation Rate of Taitel & Dukler Flow Pattern Transition Lines

Air-Water Flow in a Horizontal 2-in. Pipe

V_{sl}	V_{sg}	ϕ-ss	ϕ-sw	ϕ-slug	ϕ-DB	ϕ-ANN1	ϕ-ANN2	T-D-FP
[m/s]	[m/s]	W/m	W/m	W/m	W/m	W/m	W/m	FP
0.14351	0.01	0.001718	0.001716	0.00204	0.002068	0.070243	0.006757	S-S_S-W
0.13757	0.01585	0.001595	0.001591	0.001934	0.001981	0.022526	0.002058	S-S_S-W
0.13164	0.02512	0.001515	0.001509	0.001894	0.001972	0.002149	0.002053	S-S_S-W
0.12571	0.03981	0.00149	0.00148	0.001951	0.002078	0.002311	0.002148	S-S_S-W
0.11978	0.0631	0.001536	0.001523	0.002162	0.002372	0.00267	0.002395	S-S_S-W
0.1134	0.1	0.00167	0.001656	0.002613	0.00297	0.003357	0.002857	S-S_S-W
0.10681	0.15849	0.00196	0.001941	0.00352	0.004152	0.00485	0.003761	S-S_S-W
0.13889	0.25119	0.004772	0.004738	0.009576	0.010823	0.013381	0.009647	S-S_S-W
0.15076	0.39811	0.008405	0.008407	0.019337	0.021815	0.029087	0.018892	S-S_S-W
0.1613	0.63096	0.015276	0.015464	0.040341	0.045476	0.06699	0.038488	S-S_S-W
0.16899	1	0.028579	0.029477	0.085845	0.09691	0.161432	0.080968	S-S_S-W
0.09996	1.58489	0.028357	0.03107	0.090434	0.11584	0.20934	0.100031	S-S_S-W
0.04395	2.51189	0.034609	0.041886	0.063631	0.125643	0.246439	0.125819	S-S_S-W

Energy Dissipation Rate of Taitel & Dukler Flow Pattern Transition Lines …

V_{sl}	V_{sg}	ϕ-ss	ϕ-sw	ϕ-slug	ϕ-DB	ϕ-ANN1	ϕ-ANN2	T-D-FP
2.38867	0.01	4.42489	4.42242	5.009424	4.849324	834.191	67.85484	INT_D-B
2.5293	0.01585	5.183129	5.177146	5.916224	5.71304	1318.731	32.13437	INT_D-B
2.68311	0.02512	6.110791	6.095411	7.037859	6.777387	2102.649	16.68997	INT_D-B
2.84131	0.03981	7.178254	7.14104	8.355784	8.022863	3289.865	8.088773	INT_D-B
3.0083	0.0631	8.432396	8.371351	9.958955	9.531092	5068.969	9.577461	INT_D-B
3.41699	0.1	12.07313	11.96776	14.54936	13.81613	11427.72	13.912	INT_D-B
3.74219	0.15849	15.67174	15.50962	19.3295	18.23235	19545.33	18.41265	INT_D-B
4.09814	0.25119	20.465	20.21571	25.95679	24.29149	30406.28	24.53871	INT_D-B
4.48047	0.39811	26.82915	26.45555	35.22388	32.66036	40839.65	33.00154	INT_D-B
4.90234	0.63096	35.68166	35.12121	48.90826	44.83675	50.165	45.28715	INT_D-B
5.3418	1	47.71666	46.89821	69.08758	62.46851	37684.66	62.87242	INT_D-B
5.8252	1.58489	65.38959	64.2008	101.5388	90.19348	107.6273	90.10182	INT_D-B
6.32617	2.51189	91.25814	89.5996	155.0255	134.6004	162.457	132.8384	INT_D-B
6.84473	3.98107	130.8871	128.7285	249.2067	210.0204	248.9217	203.6771	INT_D-B
7.37207	6.30957	194.105	191.717	425.9453	345.2462	386.5434	326.5109	INT_D-B
7.87305	10	297.3381	296.1294	775.2279	597.7427	607.1081	548.4449	INT_D-B
8.34766	15.84893	475.3383	480.1204	1438.258	1096.798	978.5496	1488.896	INT_D-B
8.69922	25.11887	783.2591	809.3516	2741.262	2098.549	1627.682	3213.977	INT_D-B
8.91016	39.81072	1343.571	1437.42	5427.395	4179.758	2932.575	6669.171	INT_D-B

Energy Dissipation Rate of Barnea Flow Pattern Transition Lines

V_{sl}	V_{sg}	ϕ-ss	ϕ-sw	ϕ-slug	ϕ-DB	ϕ-ANN1	ϕ-ANN2	Barnea
0.18711	2.83708	0.152203	0.168634	0.55235	0.619587	0.638203	0.522306	IN_AN
0.19289	3.16228	0.189075	0.211262	0.694294	0.774166	0.80474	0.656567	IN_AN
0.24314	3.98107	0.36077	0.405618	1.378591	1.477058	1.535492	1.252664	IN_AN
0.3065	5.01187	0.688431	0.779009	2.735599	2.818321	2.927265	2.389932	IN_AN
0.3864	6.30957	1.313798	1.496601	5.433066	5.377955	5.585197	4.559623	IN_AN
0.48714	7.94328	2.507287	2.876004	10.80967	10.26253	10.65645	8.699023	IN_AN
0.61418	10	4.785325	5.528555	21.55841	19.58475	20.33197	16.59611	IN_AN
0.77439	12.58925	9.133637	10.6306	43.10791	37.37699	44.3663	36.10267	IN_AN
0.97643	15.84893	17.43373	20.44713	86.4227	71.33604	105.4906	85.55341	IN_AN
1.23125	19.95263	33.27889	39.34075	169.6699	136.1566	229.5295	185.7725	IN_AN
1.55261	25.11887	63.52723	75.71363	323.9864	259.8839	476.9916	385.2687	IN_AN
1.95793	31.62278	121.2732	145.7587	618.6417	496.0661	958.8781	774.2755	IN_AN
2.46915	39.81072	231.5236	280.6897	1181.258	946.9261	1873.586	1512.429	IN_AN
3.11392	50.11873	442.0109	540.6743	2255.498	1807.602	3562.289	2873.623	IN_AN
3.92719	63.09575	843.8988	1041.763	4306.663	3450.683	6579.996	5314.775	IN_AN
4.95294	79.43284	1611.22	2007.811	8223.085	6587.402	11757.56	9543.245	IN_AN
6.24672	99.999	3076.24	3870.666	15700.75	12575.46	20350.42	16602.96	IN_AN

Prediction of Flow Patterns Transition Line Using Equal Energy Dissipation Concept

- **Method**
  - **Calculate Dissipation Energy Rates (ϕ_1 and ϕ_2) for Any Two Flow Patterns at Different Operational Conditions**
  - **If ϕ_1 and ϕ_2 are Within Certain Range (< 3%) Accept it as Solution for the Transition Line**

$$\phi_1 = (\Delta P_{T1} - \rho_H g \sin(\theta)) V_m A_P$$

$$\phi_2 = (\Delta P_{T2} - \rho_H g \sin(\theta)) V_m A_P$$

  - **At the Transition Line and for the Same Operational Conditions (v_{SG} and v_{SL})**

$$\Delta p_{T1} = \Delta p_{T2}$$

Bubble – Dispersed Bubble Transition (BU-DB)

- **Dispersed Bubble Flow Pattern**
  - Homogeneous Flow Model to Calculate the Total Pressure Gradient
- **Bubble Flow**
  - First, Calculate In-Situ Gas Void Fraction By Solving the Bubble Rise Velocity Iteratively (Modified Harmathy By Zuber and Hench (1962))

$$1.53\left[\frac{g(\rho_L-\rho_G)\sigma}{\rho_L^2}\right]^{0.25}(1-\alpha)^{0.5}\sin(\theta)=\frac{v_{SG}}{\alpha}-1.2v_m$$

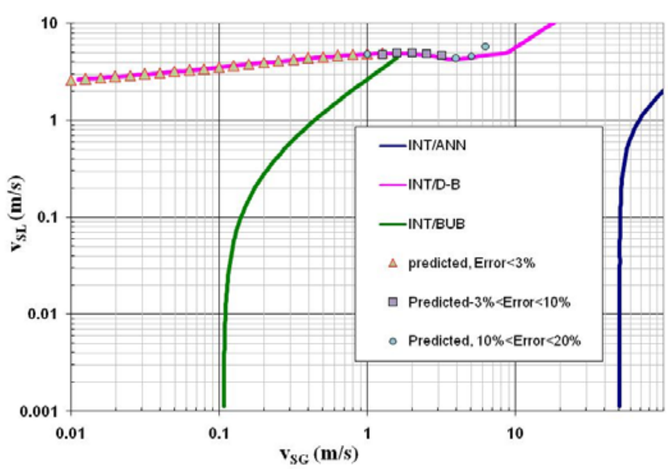
  - Calculate Total Pressure Gradient

$$\rho_m=\rho_L(1-\alpha)+\rho_G\alpha \qquad \mathrm{Re}_m=\frac{\rho_m v_m d}{\mu_m}$$

$$\mu_m=\mu_L(1-\alpha)+\mu_G\alpha \qquad f_m=\frac{0.3164}{\mathrm{Re}_m^{0.25}}$$

$$\Rightarrow \quad -\left.\frac{dp}{dL}\right|_T=\rho_m g\sin(\theta)+\frac{f_m\rho_m v_m^2}{2D}$$

Bubble – Dispersed Bubble Transition and Barnea Flow Pattern Model (Air-Water, Vertical 6-in. Pipe)



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Bubble – Dispersed Bubble Transition – Analytical Solution

- Simplified Form of In-Situ α Equation namely, without Zuber and Hench (1962) Modification to Calculate Void Fraction α Explicitly for Bubble Flow as

$$\alpha = v_{SG} \Big/ \left\{ 1.53 \left[\frac{g(\rho_L - \rho_G)\sigma}{\rho_L^2} \right]^{0.25} \sin(\theta) + 1.2(v_{SL} + v_{SL}) \right\}$$

- Only v_{SL} and v_{SG} at the Transition Line Would Satisfy The Following Conditions

$$\Delta P_{T-BU} = \Delta P_{T-DB} \qquad \rho_m g \sin(\theta) + \frac{f_m \rho_m v_m^2}{2d} = \rho_h g \sin(\theta) + \frac{f_h \rho_h v_m^2}{2d}$$

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Bubble – Intermittent Flow Transition

- Intermittent Flow Results
  - Obtained from Unified Model
- Bubble Flow
  - Obtained from Proposed Method
- Test Case
  - Air-Water Vertical Flow in a 6-in. Pipe

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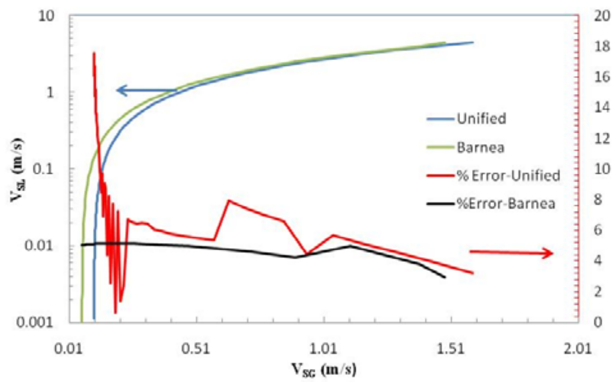
Bubble – Intermittent Flow Transition …

- Error is the Percentage Between the Total Pressure on Both Sides of the Transition



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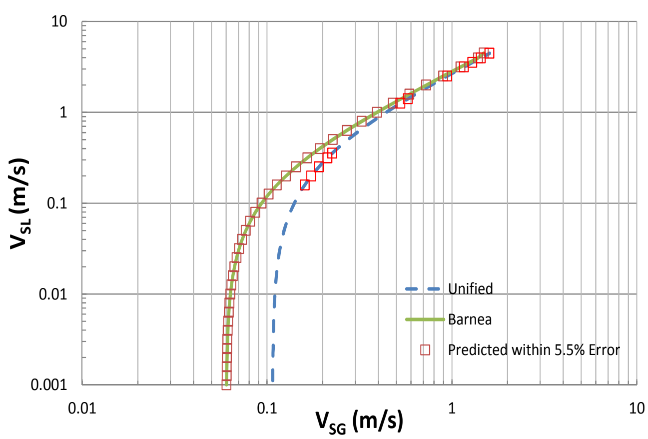
Bubble – Intermittent Flow Transition …



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Conclusions

- Flow Pattern Predictions in Two-Phase Flow can Be Improved by Applying Equal Rate of Dissipation Energy at the Transition
- Flow Patterns may Be Detected Using the Minimum Energy Dissipation Point If and Only If the Total Pressure Drop is Predicted with High Accuracy
  - Prediction Tools for Pressure Drop Still Far from Sufficient Accuracy Level for Most of the Flow Patterns

Future Work

- Using the Minimum Energy Dissipation Approach Modeling of
  - Gas-liquid Stratified Flow Including Inclination Angle Effect
  - Slug and Annular Flows
  - Churn Flow
- Integrating All Models Together in One Prediction Program

Questions

Application of Minimum and Equal Energy Dissipation Concepts in Multiphase Flow Predictions

Al-Sarkhi, A., Pereyra, E., Sarica, C.

Objective

The main objective of this project is to model multiphase flow behavior using minimum and equal energy dissipation concepts.

Introduction

The force balance or momentum equations approach to solve fluid flow problems are relatively complex and require several closure relationships. In many cases, the momentum-based models hide the physical aspect of the problem and may result in singularities especially at the transition lines. The energy minimization approach or the minimum rate of energy dissipation approach is much easier in many problems and provides more physics and smooth transitions across different flow patterns.

Chih and Charles (1986) stated that "The general theory of minimum energy can be stated as: for a closed and dissipative system in a static stable equilibrium condition, its total energy is at its minimum value," and "The general theory of minimum rate of energy dissipation can be stated as: for a closed and dissipative system in a static stable equilibrium condition, its total rate of energy dissipation is at its minimum value."

Application of this theory was demonstrated by Chih and Charles (1986) for dynamic equilibrium of open channel flow and laminar single-phasesingle-phase flow in a pipe. The solution obtained by the minimum energy dissipation approach agrees very well with that obtained with the conventional approach.

Predictions of gas-liquid flow characteristics, such as pressure gradient, flow patterns, liquid holdup, and gas void fraction are important in all engineering applications. Several mechanistic, analytical and theoretical investigations for gas-liquid flow modeling have been conducted. However, the physics of the phenomena have not been completely understood, and existing models are usually quite complex and its prediction uncertainty sometimes reaches several orders of magnitude. Predictive models have evolved over several decades from empirical correlations, to comprehensive mechanistic models and finally to unified mechanistic models. Taitel and Dukler (1976) constructed a traditional model for stratified flow in horizontal and slightly inclined pipes based on equilibrium stratified flow. Barnea (1987) developed a unified model for all inclination angles. Xiao (1990) developed a comprehensive mechanistic model for near-horizontal pipes. Gomez (2000) proposed a unified mechanistic model for all inclination angles. Zhang *et al.* (2003) developed a unified mechanistic model based on slug dynamics. Unified models are applicable for all inclination angles and flow patterns. In general, these widely used models consider mass and momentum equations which required auxiliary relationships to fully close the models.

Only a few attempts have been made to include energy equations in the available mechanistic models. Brauner *et al.* (1996) predicted interface curvature in a stratified two-phase system considering potential and surface energy. Chakrabarti *et al.* (2005) developed a liquid-liquid horizontal flow model for segregate flow patterns using minimum energy concept and combined momentum equation. This model predicts pressure gradients for stratified smooth and stratified wavy flow patterns. The model prediction was validated with their own experimental data and the Lovick and Angeli (2004) data. Sharma *et al.* (2011) developed a comprehensive model for the oil-water two-phase flow using the energy minimization concept. The model predicts well all flow patterns described in Trallero *et al.* (1997) as well as liquid holdup and pressure gradient. The model calculates total energy for all flow patterns selecting the flow pattern corresponding to the minimum energy.

Quemada (1977) proposed a rheological model for a dispersed system using the minimum energy dissipation principle. The author considered that all entropy production came from viscous dissipation. Yang and Song (1985) postulated that alluvial channels accommodate its velocity, slope, depth and roughness in such a way that a minimum energy dissipation rate is spent to transport water and sediments.

Taitel *et al.* (2003) presented a study of gas-liquid flow in parallel pipes. Their theoretical calculations showed that there are infinite steady-state solutions to the splitting ratios, but the one observed is the one that gives a minimum pressure drop. Recently, Dabirian (2012) successfully applied minimum energy dissipation to predict the splitting ratio in parallel pipelines.

Lee *et al.* (2013) modeled stratified flow hydrodynamics in horizontal pipes using the minimum energy dissipated concept. It was demonstrated that the minimum dissipated energy corresponds to the minimum total pressure gradient in a pipe section.The addition of this new equation (minimum energy dissipation) allows the computation of the liquid level in stratified flow without the use of a closure relationship for the interfacial friction factor. The liquid level which makes the pressure gradient minimum is the solution.

Modeling

A: Equal Energy Dissipation in Single-Phase Flow Systems: Laminar to Turbulent Flow Transition

For a given head loss between two points, the total energy dissipation rate Φ can be written as

$$\Phi = \Delta P \times Q = \gamma \times Q \times h_L \,, \qquad (1)$$

where $\Phi, \Delta \mathrm{P}, \mathrm{Q}, \gamma, h_L$ are the total energy dissipation rate, the pressure drop, flow rate, fluid specific weight, and the head loss, respectively.

The head loss, h_L, can be related to the friction factor, *f*. The friction factor can be written as

$$f = C\,\mathrm{Re}^n \,, \qquad (2)$$

where *C* and *n* are the flow regime (laminar or turbulent) dependent constants.For laminar flow, $n = -1$ and $C = 64$. For turbulent flow in smooth pipes, Blasius' equation can be used with $n = -0.25$ and $C = 0.3164$ (for *Re* range from 3000 to 100,000). Moreover, for turbulent flow, different values for *C* and *n* are available for different ranges of the Reynolds number. For all practical purposes, the correlation covering the widest range of the Reynolds number is $n = -0.2$ and $C = 0.184$.

Thus, using the first set of constants for *C* and *n*, the total rate of energy dissipation for laminar and turbulent single-phase flows can be written in terms of Reynolds' Number, *Re*, as

$$\Phi_L = const. \times 64\,\mathrm{Re}^2 \,. \qquad (3)$$

$$\Phi_T = const. \times 0.3164\,\mathrm{Re}^{2.75} \,. \qquad (4)$$

By equating the rate of energy dissipation at the transition point, the critical Reynolds number for the transition will be $Re = 1187$. However, using the second set of constants for *C* and *n*, the rate of energy dissipation equation yields the following equations for the energy dissipation rate in laminar and turbulent flow:

$$\Phi_L = const. \times 64\,\mathrm{Re}^2 \,. \qquad (5)$$

$$\Phi_T = const. \times 0.184\,\mathrm{Re}^{2.8} \,. \qquad (6)$$

By equating the rate of energy dissipation at the transition point, the critical *Re* for the transition will be $Re = 1502$.

However, the laminar-turbulent transition always occurs at higher Reynolds numbers and nature prefers the laminar flow near the critical Reynolds number. Joseph (1976) predicted the critical Reynolds number of 81.5 using the method of energy Eigen value for Hagen-Poiseuille flow. Joseph suggested that there may be three distinct types of flow: (a) one in which eddies cannot exist, corresponding to truly viscous flow; (b) one in which eddies may exist, due to an initial disturbance, but cannot be sustained in the pipe, the initial eddies therefore ultimately disappearing; (c) one in which eddies once generated will be maintained without decrement throughout the pipe, corresponding to truly turbulent flow (where Re >2000). In fact, the value of the critical Reynolds number of 1502 is closer to the value of 2000 than any of those predicted by other methods in literature.

B: Multiphase Flow System

The total dissipation energy (given in W/m) due to the friction in two-phase flow system in pipes can be written based on conservation equations of one-dimensional two-fluid models as in Lei (2013) in Eq. (7).

$$\Phi = v_m \times (-dp/dx - \rho_h g \sin\theta) A_p \,, \qquad (7)$$

where ρ_h, v_m, dp/dl, θ, and A_p are the homogeneous mixture density, mixture velocity, total pressure gradient, angle of inclination and the pipe cross-sectional area, respectively. The homogeneous mixture density is defined as

$$\rho_h = \rho_G \lambda_G + \rho_L (1 - \lambda_G) \,. \qquad (8)$$

The relation between pressure drop and pressure gradient is $\Delta p / L = -dp/dx$ where Δp is the pressure drop (positive quantity), and L is the length of the pipe section.

Therefore, Eq. (9) can be written in terms of the total pressure drop as

$$\Phi = v_m (\Delta p / L - \rho_h g \sin\theta) A_p \,, \qquad (9)$$

where the Δp/L is the total pressure drop per unit length, λ_G is the gas volume fraction (v_{SG}/v_m), and v_m is the mixture velocity ($v_m = v_{SG} + v_{SL}$).

The total pressure drop is the summation of the frictional part and the gravitational part (ignoring the accelarational pressure drop)

$$\Delta p / L = \Delta p / L_f + \rho_{TP} g \sin\theta \,, \qquad (10)$$

where $\Delta p / L\big|_f$, ρ_{TP} are the frictional pressure drop and the two phase mixture density based on the actual liquid holdup (H_L) as in Eq. (11)

$$\rho_{TP} = \rho_L H_L + \rho_G (1 - H_L)\,. \qquad (11)$$

The total energy dissipation rate suggested by Eq. (7) is a combination effect of the frictional pressure drop, gravity, density and pipe inclination and can be re-written in terms of frictional pressure drop as in Eq. (12).

$$\Phi = v_m (\Delta p / L_f + (\rho_{TP} - \rho_h) g \sin\theta) A_p \,.(12)$$

Lei *et al.* (2013) also derived the same equation, Eq. (12), for energy dissipation rate of intermittent flow in pipes.

Two procedures can be followed to solve multiphase flow problems and to predict the flow pattern in two-phase flow. The first procedure is that for all flow patterns, the total rate of energy dissipation must be calculated at the same operational conditions, and then the minimum value is accepted as the solution.

The second procedure requires that for all flow patterns the total rate of energy dissipation must be calculated and then a search for the locations where the rate of energy dissipations are equal for different flow patterns must be located. This method will detect the flow pattern transition lines. At the transition line the energy dissipation rates must be equal even though they are calculated considering the two different flow patterns.

As for the first procedure, a scan over the whole matrix of v_{SL} and v_{SG} was performed and did not work well because of the sensitivity to models and closure relationships. In conclusion, selecting the flow pattern which has the minimum energy dissipation rate procedure cannot be used for flow pattern detection at this time since it will almost always be stratified for horizontal flow and dispersed bubble flow in vertical flow. Another problem when using this procedure is that the differences, sometimes, between the energy dissipation values are very small which lies within the uncertainty of the models used to calculate the pressure gradient.

In the following section the second procedure will be tested.

Model Validation

1) Experimental Data of Andritsos (1986)

The experimental data of Andritsos (1986) have been used to identify the energy dissipation rate at points very close to the flow pattern transition line.The energy dissipation rate is almost the same at the points very close to the transition lines. Therefore, they should have a smooth transition, and the rate of energy dissipation at the line should be unique.

2) Model to Model Comparison

The energy dissipation rate was calculated for different flow patterns (in vertical and horizontal configurations) along the transition line predicted by Taitel and Dukler, TUFFP Unified and Barnea flow pattern maps. The energy dissipation rates in many cases are equal at the transition lines.

3) Prediction of Flow Patterns Transition Line Using Equal Energy Dissipation Concept

First, the dissipation energy rates are calculated for two-phase flow patterns (ϕ_1 and ϕ_2) at different operational conditions. Then, the operating points with equal ϕ or within a certain range (<3%) of $\Delta\phi$ are considered as the solution for the transition line. ϕ_1 and ϕ_2 are defined as follows:

$$\phi_1 = (\Delta p_{T1} - \rho_H g \sin(\theta)) V_m A_P \,.$$

$$\phi_2 = (\Delta p_{T2} - \rho_H g \sin(\theta)) V_m A_P \,. \qquad (13)$$

At the transition line and for the same operational conditions (v_{SG} and v_{SL}) then equating ϕ_1 and ϕ_2 simply gives

$$\Delta p_{T1} = \Delta p_{T2}\,. \qquad (14)$$

The bubble-dispersed bubble transition for vertical flow was accurately predicted, and a simplified closed-form solution for the transition line was obtained. Moreover, the bubble-intermittent flow and the intermittent-annular flow transition lines were reasonably predicted.

Conclusions

The following conclusion can be drawn from the present work:

1) Flow pattern predictions in two-phase flow can be improved by applying the equating rate of dissipated energy at both sides of a transition line.
2) Flow patterns may be detected using the minimum energy dissipation point if and only if the prediction of the total pressure drop reaches a high accuracy level.
3) The prediction tools for pressure drop are still far behind the 100% confidence for most of the flow patterns.

Future Work

- Using the minimum energy dissipation approach modeling of:
    - Gas-liquid stratified flow including inclination angle effect
    - Slug and annular flows
    - Churn flow

- Integrating all models together in one prediction program

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Fluid Flow Projects

Unified Interfacial Friction Factor for Annular, Churn and Slug Flows

Al-Sarkhi, A.,
Pereyra, E., Sarica, C.

Outline

- Objectives
- Introduction
- Modeling
- Prediction of Flow Pattern Transition
- Future Tasks
- Conclusions

Objective

- Develop a Unified Interfacial Friction Factor Closure Model for Annular, Wispy Annular, Churn and Pseudo-Slug or Slug Flows

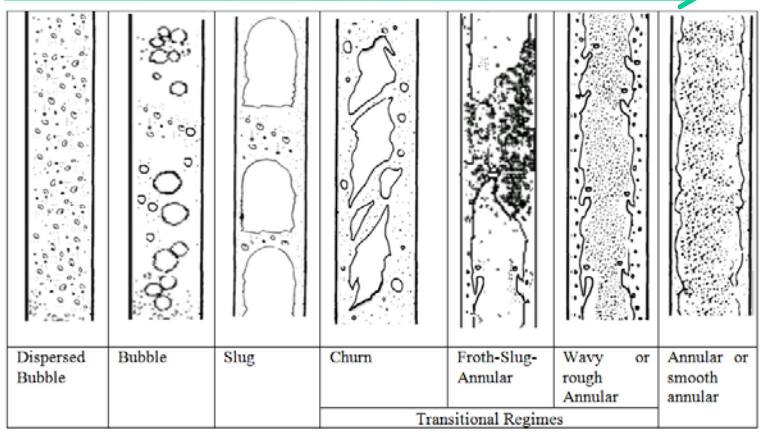
Introduction

- Hewitt (2012) Made an Appeal for the "Churn" and "Wispy Annular" Patterns to Be Given More Attention
- Less Attention is a Reflection of Their Complexity and not a Reflection of Their Industrial and Technological Importance
- Uncertainty in Pressure Gradient Calculation Using Current Churn to Slug Flow Models is Very High
- There is a Need for More Investigation in These Regions

Introduction …

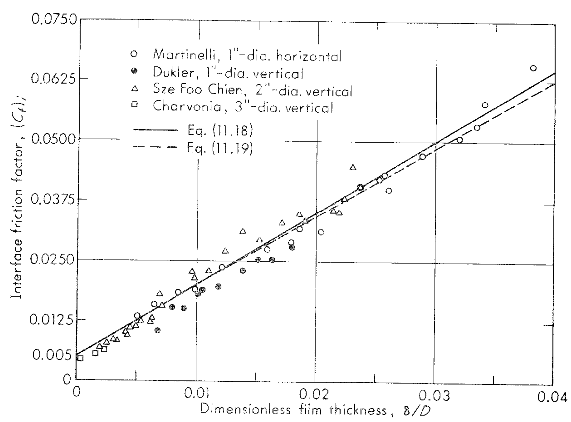
- **Transition from Annular to Slug Flow**

Increasing Gas Flow Rates or Decreasing Liquid Flow Rates



Introduction …

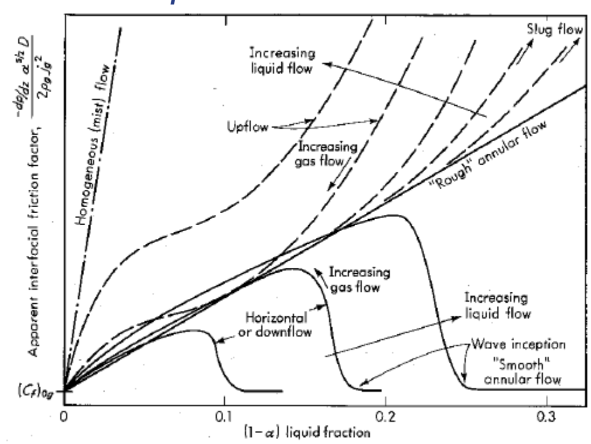
- **Wallis (1969)**
  - **Similarity Between His Interfacial Friction Factor (f_i) Correlation and Rough Surface Friction Factor (f_w) Correlation in Pipes**



$$f_i = 0.005(1 + C(\delta / d)) \qquad f_w = 0.005(1 + 75\,k_s / d)$$

Introduction …

- Wallis (1969): Coherent Structure is a Function of f_i and Film Thickness

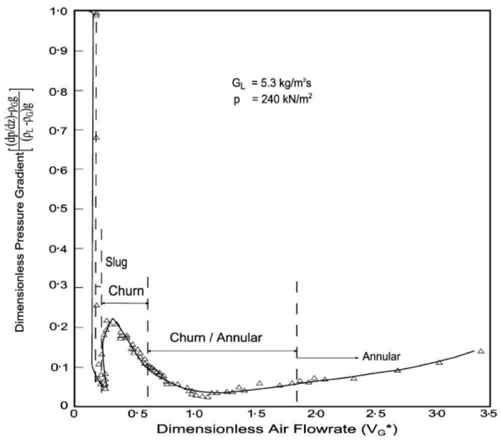


Introduction …

- **Wallis's (1969) Correlation did not Accurately Predict Interfacial Friction Factor Especially for Thicker Films (Fore *et al.* 2000)**
- **Several Correlations have been Suggested to Improve Wallis's (1969) Correlation**
  - Asali *et al.* (1985) and Henstock and Hanratty (1976)
  - Almost All Modifications Kept the Structure of the Correlation
  - Only Constants 0.005 and *C* were Replaced

Introduction …

- Hewitt (2012) Noticed the Strong Relation between the Pressure Gradient and the Flow Pattern Transition from Annular Flow to Slug Flow



$$V_G^* = v_{SG}\rho_G^{1/2}\left(gd(\rho_L - \rho_L)\right)^{-1/2}$$

New Unified Interfacial Friction Factor Closure Relationship

- New Proposed Interfacial Friction Factor for Flow Patterns from Annular to Slug Flow was Obtained by Adjusting the Parameter *C* and the 0.005 of the Wallis (1969) Correlation

$$f_I = f_C\left(1 + C\frac{\delta_L}{d}\right)$$

- Adjustment of *C* is Made by Using the Equal Energy Dissipation Concept at the Transition Line

New Unified Interfacial Friction Factor Closure Relationship …

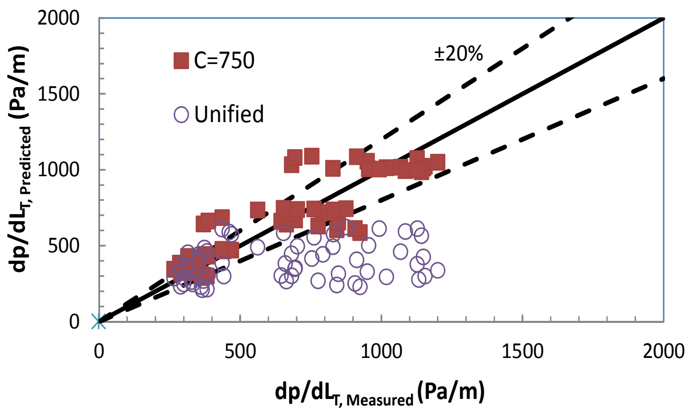
C	Flow Pattern	Configuration
750	Annular	All Inclination Angles from Vertical to Horizontal
1270	Wavy Annular	Vertical and Inclined
21000	Slug and Churn Flow	Vertical and Inclined
25	Slug and Churn Flow	Horizontal

Model Validation – Guner (2012) Data

- Air-Water Flow in a Vertical and Sharply Inclined 3-in. ID Pipes
- Annular, Annular Wavy, and Churn Flow Data

Model Validation – Guner (2012) Data

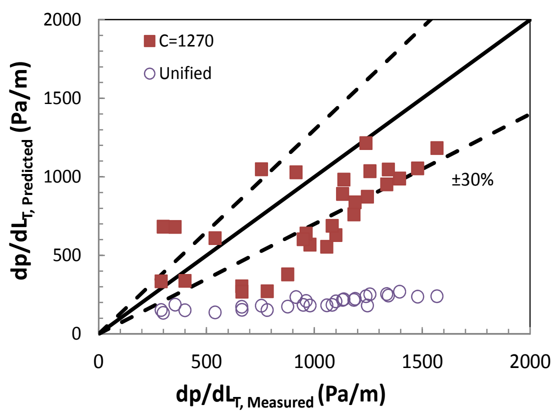
- Annular



$20 < v_{SG} < 40$; $0.01 < v_{SL} < 0.1$; Θ from 45° to 90 °

Model Validation – Guner (2012) Data …

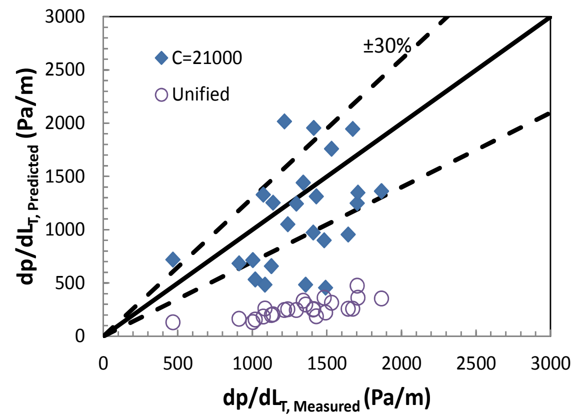
- Wavy Annular Flow



$10 < v_{SG} < 16$, $0.01 < v_{SL} < 0.1$; Θ from 45° to 90°

Model Validation – Guner (2012) Data …

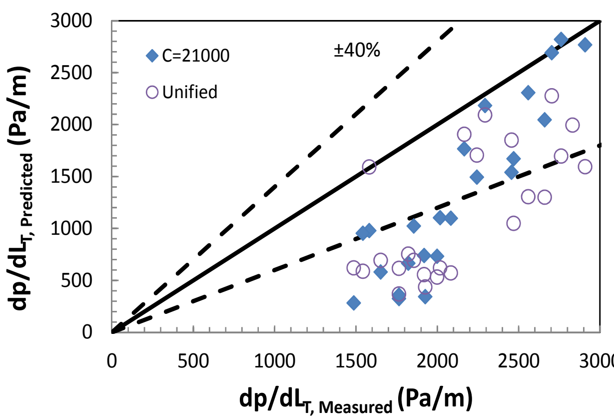
- Churn Flow



$5<v_{SG}<10$, $0.01<v_{SL}<0.1$ Θ from 45° to 90°

Model Validation – Guner (2012) Data …

- Slug Flow



$1.4<v_{SG}<5$, $0.01<v_{SL}<0.1$ Θ from 45 to 90

Model Validation – Guner (2012) Data …

- Ishii (1989) Entrainment Fraction Correlation Used in Proposed Model Calculations
- Average Absolute Relative Error, ε_2

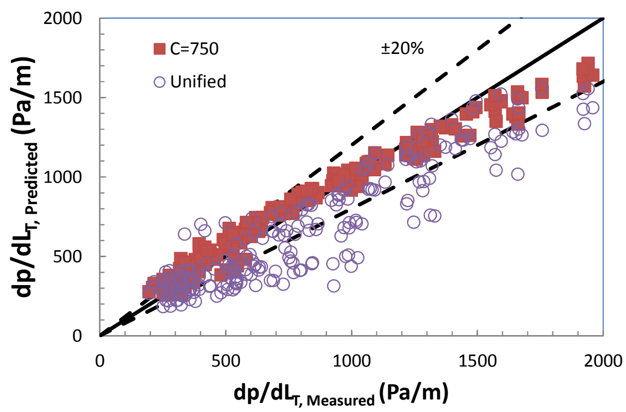
Flow Pattern	Proposed Model	Unified Model
Annular	18.2%	45.6 %
Wavy Annular	38.3%	76.5 %
Churn	32.4%	80.69%
Slug	40.7%	48.5%

Model Validation – Yuan (2011) Data

- Yuan (2011)
  - Air-Water Flow in a Vertical and Sharply Inclined 3-in. ID Pipes
  - Annular, Annular Wavy, and Churn Flow Data

Model Validation – Yuan (2011) Data …

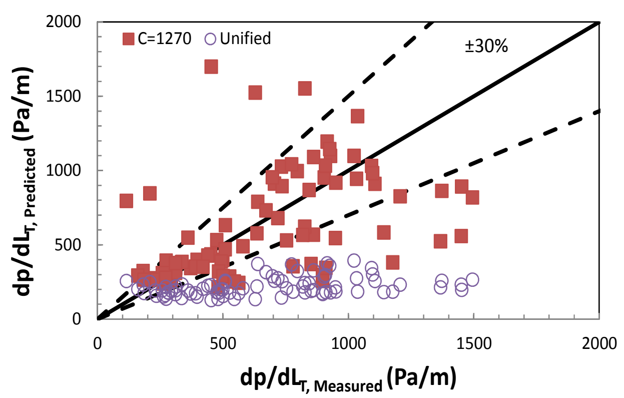
- Annular



$17<v_{SG}<80$, $0.003<v_{SL}<0.1$ Θ from 60° to 90°

Model Validation – Yuan (2011) Data …

- Intermittent Flow



$9.9<v_{SG}<32$, $0.0045<v_{SL}<0.1$ Θ from 60° to 90°

Model Validation – Yuan (2011) Data …

- Oliemans's (1986) Entrainment Fraction Was Used in Proposed Model
- Average Absolute Relative Error, ε_2

Flow Pattern	Proposed Model	Unified Model
Annular	12.3%	23.1%
Intermittent	42.7% %	60.99%

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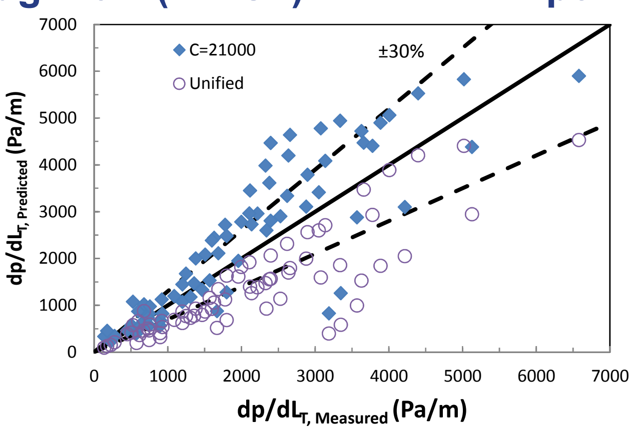
Model Validation – Felizola (1992) Data

- Slug Flow (Air-Oil) in 2-in. ID Pipe



$0.39<v_{SG}<2.02$, $0.05<v_{SL}<0.56$ Θ from 10° to 90°

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Model Validation – Felizola (1992) Data …

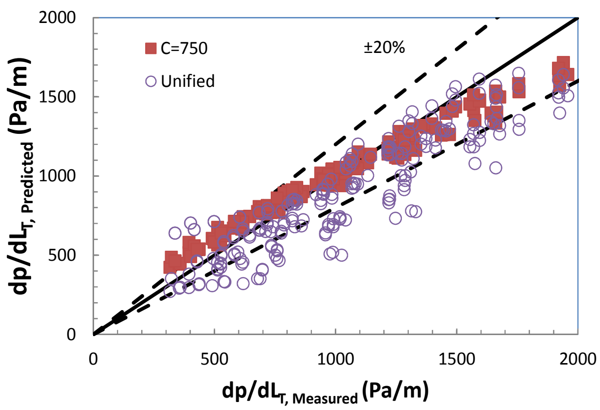
- Ishii's (1989) Entrainment Fraction Was Used in Proposed Model
- Average Absolute Relative Error, e_2

$$\varepsilon_{2\text{- model}}=33.4\%$$

$$\varepsilon_{2\text{- Unified}}=35.4\%$$

Model Validation – Magrini (2009) Data

- Slug Flow (Air-Water) in 3-in. ID Pipe



$36<v_{SG}<60$, $0.0035<v_{SL}<0.04$ Θ from 0° to 90°

Model Validation – Magrini (2009) Data ..

- **Oliemans's (1986) and Unified Model Entrainment Fraction Correlations were Used in Proposed Model**
- **Average Absolute Relative Error, ε_2**

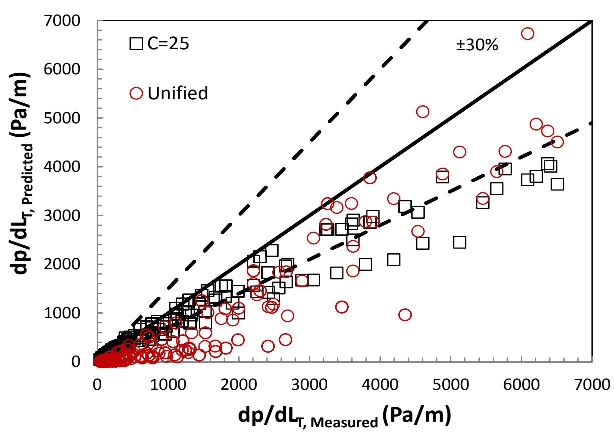
$\varepsilon_{2\text{-model}}$=12.43% with Oliemans FE

$\varepsilon_{2\text{-model}}$=10.52% with TUFFP FE

$\varepsilon_{2\text{-Unified}}$=17.8%

Model Validation – Brito (2012) Data

- **Slug Flow (Air-Oil) in 2-in. ID Pipe for Oil Viscosities between 39 cp and 166 cp**



Model Validation – Brito (2012) Data …

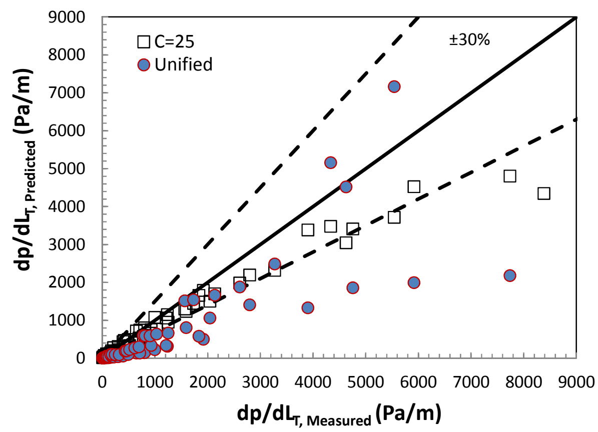
- Ishii's (1989) Entrainment Fraction Was Used in Proposed Model
- Average Absolute Relative Error, ε_2

$$\varepsilon_{2\text{- model}} = 18.3\%$$

$$\varepsilon_{2\text{- Unified}} = 68\%$$

Model Validation – Kokal (1989) Data

- Air-Oil Slug Flow in 1-in. ID Horizontal Pipe for Oil Viscosity of 7 cp



Model Validation – Kokal (1989) Data …

- Olieman's (1986) Entrainment Fraction was Used in Proposed Model
- Average Absolute Relative Error, ε_2

$$\varepsilon_{2\text{- model}} = 25\%$$

$$\varepsilon_{2\text{- Unified}} = 57.7\%$$

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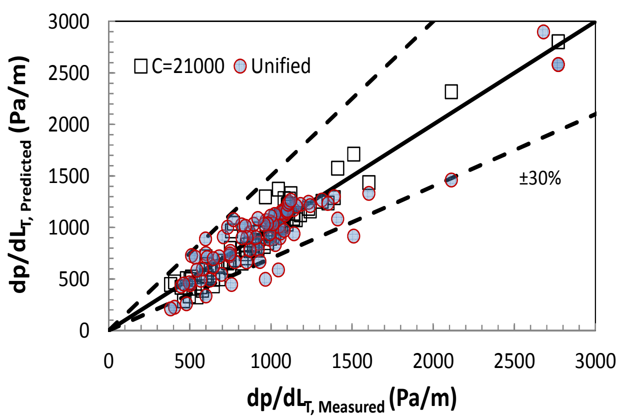
Model Validation – Kokal (1989) Data …

- Air-Oil Slug Flow in 1-in. ID 9° Inclined Pipe for Oil Viscosity of 7 cp



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Model Validation – Kokal (1989) Data …

- Wallis's (1969) Entrainment Fraction was Used in Proposed Model
- Average Absolute Relative Error, ε_2

$\varepsilon_{2\text{- model}}$= 12.11%

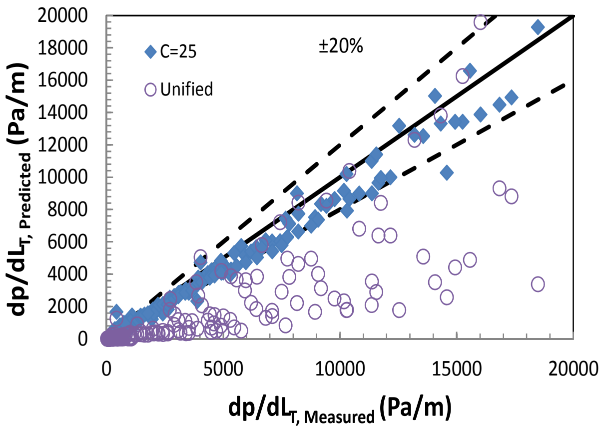
$\varepsilon_{2\text{- Unified}}$=15.12%

Model Validation – Gokcal (2005) Data

- 183 Data Points, Slug Flow of Air-Oil in a 2-in. ID Horizontal Pipe
- Different Entrainment Fraction Models were Tested
- $0.01<v_{SL}<1.76$; $0.095<v_{SG}<20.3$
- $177cp<\mu_{oil}<601cp$

Model Validation – Gokcal (2005) Data …

- Proposed Model Using TUFFP FE Model



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Model Validation – Gokcal (2005) Data …

- Effect of Entrainment Fraction Model on Pressure Drop

F_E -Model	ε_{2-} Proposed Model, %
Ishii	17.8
Oliemans	31.9
Wallis	18
Pan & Hanratty	19.19
TUFFP	17.47

$\varepsilon_{2\text{- Unified}} = 73.8\%$

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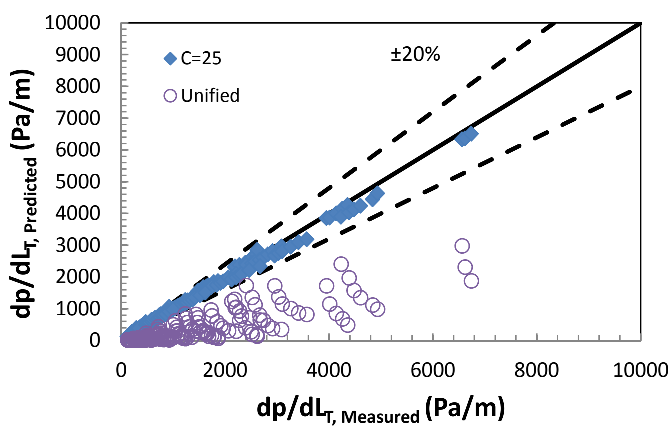
Model Validation - Gokcal (2008) Data

- Slug Flow of Air-Oil in a 2-in. ID Horizontal Pipe
- Different Entrainment Fraction Models were Tested
- $0.05<v_{SL}<0.8$; $0.1<v_{SG}<2.17$
- $178cp<\mu_{oil}<600cp$

Model Validation – Gokcal (2008) Data …

- Proposed Model Using Ishii FE Model



Model Validation – Gokcal (2008) Data

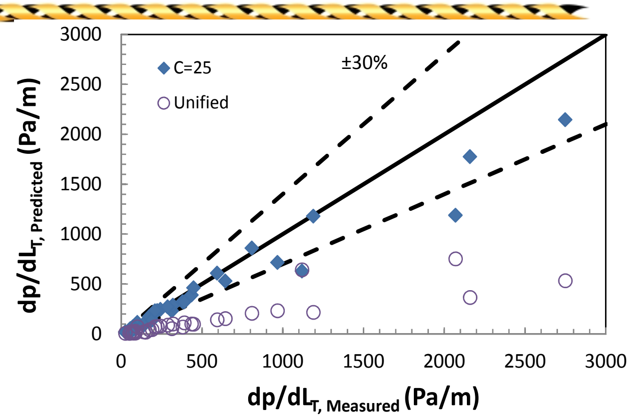
- Effect of Entrainment Fraction Model on Pressure Drop

F_E -Model	ε_{2-} Proposed Model, %
Ishii	6
Oliemans	13.28
Wallis	6.05
Pan & Hanratty	6.06
TUFFP	5.09

$\varepsilon_{2\text{- Unified}} = 80.6\%$

Model Validation: *(Andritsos 1989)*

34 data points, 19 in the slug flow region and 15 in the pseudo-slug air-water in 0.025-m and 0.095-m horizontal pipelines



$\varepsilon_{2\text{-model}} = 19.2\%$, $\varepsilon_{2\text{-Unified}} = 75.4\%$

$0.06 < V_{SL} < 0.3$; $1.16 < V_{SG} < 25.78$

Olieman F_E Model

Conclusions

- Proposed Wallis (1969) Type Interfacial Friction Factor Correlation Implemented in an Annular Flow Model can be Used to Predict Pressure Drop of Annular, Wavy Annular, Churn and Slug Flows Efficiently
- Pressure Gradient of Slug Flow is Modeled Very Well with the Proposed Model, Especially for High Viscosity Liquid
  - Slug Flow Structure of High Viscosity Liquid is Different from the that of Low Viscosity Liquid Which can be Considered Closer to Annular Flow

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Conclusions …

- Present Analysis Demonstrates the Coherent Structure of the Transitional Vertical Flow Patterns from Annular to Slug Flow Passing through Wispy Annular and Churn Flows
- Churn Flow and Wispy Annular Flows can be Reasonably Modeled as an Annular Flow with Constraints on Interfacial, Film Thickness and Entrainment Fraction Correlations

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Questions

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Unified Interfacial Friction Factor for Annular, Churn and Slug Flows

Al-Sarkhi, A., Pereyra, E., Sarica, C

Objective

The objective of this work is to develop a unified interfacial friction factor closure model for annular, wispy annular, churn and pseudo-slug or slug flows.

Introduction

In a two-phase flow system, mass, heat and momentum transfers are very flow pattern dependent. Classically, vertical two-phase flows have been classified into the patterns of bubbly, slug, and annular flows (Hewitt 2012). Hewitt (2012) made an appeal for the "churn" and "wispy annular" patterns to be given more attention. He called them "orphaned" flow patterns. He concluded that the flow patterns of churn and wispy annular flows deserve much more attention, and the fact that they have not received such attention is perhaps a reflection of their complexity and not a reflection of their industrial and technological importance. There is a need for more investigation into these flow patterns.

Flow in vertical pipes pass through different stages as a function of liquid and gas flow rate.

At very low liquid flow rates, the liquid film in an annular flow is covered with long, crested ripples with a steep nose at the front. The ripples are separated by an almost smooth surface and the flow apparently is similar to laminar flow. At an adequate amount of liquid flow rates, roll waves appear on the film of an annular flow. These waves are distributed in patches along the circumference of the pipe. At sufficiently higher liquid rates, these waves become large amplitude waves, disturbance waves, and may cover the whole cross-sectional area of the pipe.

Bubbly flow occurs at low gas and large liquid flow rates. A small amount of gas generally flows at the center of a vertical pipe as bubbles. As the gas flow rate increases, some of the bubbles coalesce and form long, bullet-shaped Taylor bubbles, followed by liquid slugs. As the gas flow rate continues to increases, the gas penetrates through liquid slug, forming an irregular flow structure called churn flow. With further increases in the gas flow rate, the frequency of the liquid slugs decreases significantly, resulting in frothy-slug annular flow. The frothy-slug annular and churn flow are transitional flow patterns bridging the annular flow with the slug flow. At a very high gas velocity, an annular flow configuration is observed for which the liquid phase flows as a film along the pipe wall and as droplets entrained in the gas core. Annular flow can be observed at mass qualities of around 3% or higher (Azzopardi 1986).

The interface structure between the liquid film and the gas core of an annular flow is highly dynamic and constantly changing. A general characteristic of this interface is the presence of large disturbance waves along with smaller ripple waves.

The transition from annular to slug flow passes through stages based on the interface structure or the wall roughness, changing with gas and liquid velocities and other physical properties. In fact, Wallis (1969) noticed the similarity between his interfacial friction factor correlation and the relation for the fully rough friction factors in pipes for values of Nikuradse sand-grain roughness height to pipe diameter ration less than 0.03. He observed that all individual flow pattern lines for the apparent interfacial friction factor converge to the annular flow interfacial friction factor line as the liquid holdup decreases.

Hewitt (2012) noticed the strong relation of the pressure gradient and the flow pattern transitions from annular flow to slug flow passing through the transitional flow patterns, namely, the wispy annular and churn flows.

Modeling

A: Wallis's (1969) interfacial friction factor in annular flows

Wallis (1969) suggested a correlation for the annular flow interfacial friction factor which treats the liquid film as a wall roughness. His correlation was based on a fit of four sets of annular flow data using the ratio of mean film thickness to the pipe diameter as:

$$f_i = 0.005(1 + C\frac{\delta}{d}) . \qquad (1)$$

Wallis's equation (Eq. 1) did not accurately predict the interfacial friction factor especially for thicker films (Fore *et al.* 2000). Several correlations have been suggested over the years to improve prediction of the behavior of the interfacial friction factor for large film thickness. Asali *et al.* (1985) and Henstock and Hanratty (1976) proposed modified correlations to account for the deviation of measured friction factor from the Wallis correlation. Almost all modifications have preserved the format of the Wallis correlation but changed the constants 0.005 and *C*.

B: New unified interfacial friction factor closure relationship

The newly proposed interfacial friction factor closure relationship for the flow patterns from annular to slug flow is obtained by adjusting the parameter *C* of Eq. (1). The adjustment of *C* is made by using the equal energy dissipation concept at the transition line of those flow patterns. The interfacial friction factor in the proposed relationship can be given as

$$f_i = f_C\left(1 + C\frac{\delta_L}{d}\right). \quad (2)$$

The pressure gradient for different flow patterns from annular to churn, even to pseudo-slug and slug, is calculated in a similar manner to a standard annular flow model described in Shoham (2006). Based on the equal rate of energy dissipation values at the transition line between annular and the rest of the flow patterns, the following values for constant *C* were obtained: *C*= 750 for all inclination angles from horizontal to vertical; *C*= 1270 for wavy annular in vertical and high inclination angles; *C*= 21000 for slug and churn flow in vertical and inclined pipes; and *C*= 25 for slug and pseudo-slug in horizontal pipes.

Model Validation

The proposed model for annular flow with different interfacial friction factor closure relations for the pressure gradient will be compared with different experimental data sets in this section.

1) Experimental data of Guner (2012)

Guner (2013) identified four different regimes for air-water flow in vertical and sharply inclined 0.076-m diameter pipeline. For superficial gas velocities, v_{SG} larger than 16 m/s, between 10 and 15 m/s, between 10 and 15 m/s, between 5 and 10 m/s, and less than 5 m/s, annular, wavy annular, churn and slug flows were observed, respectively.

The annular flow model is used with the interfacial friction factor (f_i) correlation given in Eq (2). The average absolute relative error, ε_2, for the annular flow data is found to be 18.2% for the proposed model, and 45.6% for the unified model. The wavy annular data, ε_2, is 38.3% for the proposed model and 76.5% for the unified model. For churn flow data, ε_2, is 32.4% for the proposed model and 80.69% for the unified model. For the slug flow data, ε_2, is 40.7% for the proposed model and 48.5% for the unified model. The Ishii (1989) correlation was used for entrainment fraction in the proposed model.

The slug and churn flow data are not in very good agreement in the vertical and sharply inclined pipes for Guner's (2013) experimental data. However, the agreement is still much better than that of the unified model.

2) Experimental data of Yuan (2011)

The air-water annular and intermittent flow data of Yuan from horizontal to vertical configuration are tested, and very good agreement with the proposal model is noticed, especially for the annular flow data using *C*= 750. In the annular flow data, ε_2, is 12.3% for the proposed model and 23.1% for the unified model. For the slug flow data, ε_2, is 42.7% for the proposed model and 60.99% for the unified model. The Oliemans (1986) correlation is used for the entrainment fraction.

3) Experimental data of Felizola (1992)

Felizola (1992) acquired air-oil slug flow data from a 0.051-m diameter pipe for inclination angles from 10 to 90 degrees. The average absolute error is 33.4% for the proposed model and 35.4% for the unified model. The Ishii (1989) correlation is used for the entrainment fraction.

4) Experimental data of Magrini (2009)

Magrini (2009) collected annular flow data using a 0.076-m ID pipe for all angles of inclination from 0 to 90 degrees. Magrini's (2009) data are used to evaluate the performance of the proposed model. For this comparison with Oliemans's (1986) entrainment model is used with the proposed model. The average relative percentage error is 12.43% for the proposed model and 17.8% for the unified model. However, when the TUFFP entrainment model is used, ε_2, is about 10.52%.

5) Experimental data of Brito (2012)

Air-oil slug flow data in a 0.0508-m diameter horizontal pipe with viscosities ranging from 39 to 166 cp were used to test the proposed model. The entrainment model of Ishii (1989) is used. The average absolute error is about 18.3%. If the TUFFP entrainment model is used, ε_2, was about 17.4%. The unified model average absolute error is about 68%.

6) Experimental data of Gokcal (2005)

Gokcal (2005) acquired air-oil slug flow data for oil viscosities ranging from 167 to 600 cp in a 0.0508-m diameter horizontal pipe. Gokcal's data are used to test the performance of the model and the influence of various entrainment fraction correlations on the proposed model. Using Ishii's (1989) entrainment model, $\varepsilon_{2\text{-model}}$ =17.8%, $\varepsilon_{2\text{-Unified}}$=73.8%; Oliemans's (1986) entrainment model, $\varepsilon_{2\text{-model}}$=31.9%, $\varepsilon_{2\text{Unified}}$=73.8%; Wallis's (1969) entrainment model,

$\varepsilon_{2\text{-model}}$=18%, $\varepsilon_{2\text{-Unified}}$=73.8%; Pan and Hanratty's (2002) entrainment model, $\varepsilon_{2\text{-model}}$=19.19%, $\varepsilon_{2\text{-Unified}}$=73.8%; TUFFP entrainment model, $\varepsilon_{2\text{-model}}$=17.47%, $\varepsilon_{2\text{-Unified}}$=73.8%. The model performance is found to be very good.

7) Experimental data of Gokcal (2008)

Gokcal (2008) acquired additional air-oil slug flow data for oil viscosities ranging from 167 to 600 cp in a 0.0508 m diameter horizontal pipe. Excellent agreement between the model predictions and the Gokcal (2008) data is found. Using Ishii's (1989) entrainment model, $\varepsilon_{2\text{-model}}$=6%, $\varepsilon_{2\text{-Unified}}$=80.6%; Oliemans's (1986) entrainment model, $\varepsilon_{2\text{-model}}$=13.28%, $\varepsilon_{2\text{-Unified}}$=80.6%; Wallis's (1969) entrainment model, $\varepsilon_{2\text{-model}}$=6.05%, $\varepsilon_{2\text{-Unified}}$=80.6%; Pan and Hanratty's (2002) entrainment model, $\varepsilon_{2\text{-model}}$=6.05%, $\varepsilon_{2\text{-Unified}}$ =80.6%; TUFFP entrainment model, $\varepsilon_{2\text{-model}}$=5.9%, $\varepsilon_{2\text{-Unified}}$=80.6%.

8) Experimental data of Andritsos (1986)

Slug flow and pseudo-slug flow data in a 0.025- and 0.095-m diameter horizontal pipe of Andritsos (1986) are tested. Oliemans's (1986) entrainment model is used. Values of $\varepsilon_{2\text{-model}}$ =19.2%, and $\varepsilon_{2\text{-Unified}}$ =75.4% are obtained. A good agreement with the data is seen.

Concluding Remarks

The following conclusions can be drawn from this work

- A new interfacial friction factor correlation is developed for annular, wavy annular, churn and slug flows.
- The proposed interfacial friction factor correlation implemented in an annular flow model can be used to predict the pressure gradient of annular, wavy annular, churn and slug flows efficiently.
- The pressure gradient of slug flow is modeled very well with the proposed model, especially for high viscosity liquid.
- The slug flow structure for high viscosity liquid may be different from that for low viscosity liquid and it can be considered closer to an annular flow structure.
- The present analysis demonstrates the coherent structure of the transitional vertical flow patterns from annular to slug flow passing through wispy annular and churn flows.
- Churn and wispy annular flows can be reasonably modeled as an annular flow with constraints on interfacial friction, film thickness and entrainment fraction correlations.

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Fluid Flow Projects

TUHOP Incorporation

Cem Sarica
Eduardo Pereyra

TUHOP Review

- TUHOP was Established in 2007 as a five-year JIP to Investigate High Viscosity Oil Multiphase Flow Behavior in Pipes
- JIP was Completed in 2012
- Needed Five Members to Fully Funded as a Stand-Alone JIP
- Only Two TUHOP Members Indicated a Desire to Continue

TUHOP Review …

- Significant Investment Made Toward Construction of a New 3-in. ID High Pressure High Viscosity Oil Facility
  - $1,000,000 in Construction & Equipment
  - Man Time not Included
- Completion of the Facility Requires $500,000
- There is A $300,000 Available Balance from TUHOP
- Need to Invest Additional $200,000 to Complete the Facility

Proposal to TUFFP Membership

- Incorporation of TUHOP into TUFFP
  - Complete the Construction of the 3-in. ID High Pressure High Viscosity Oil Facility
  - Investigate Oil-Water Flow as the First Project
- Significant Value to TUFFP
  - Will Enhance TUFFP Efforts in High Viscosity Oil Multiphase Flow

Terms of the Incorporation

- Existing TUHOP Deliverables will not Be Made Available to TUFFP Members
- TUFFP members will have the Rights to the Deliverables Generated with the New Facility

Status

- Ballot has been Sent to Membership
- Membership Unanimously Recommended the Incorporation
- University of Tulsa Approved the Incorporation
- Facility Construction Activities Started

Facility Construction Update

- All Vessels, Meters, Control Valves, Heat Exchanger and Aerial Cooler have been Purchased and are on Site
- Installation of Piping and Welding has Begun and will be Completed by December 2013

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Facility Construction Update …

- Addition of Heater to Glycol System and Refurbishing of Existing Chiller to be Completed by February 2014
- Instrumentation and Electrical will be Completed By May 2014
  - Need to Decide About Utilizing Existing Generator or Adding a Second Generator Just for the Heavy Oil Facility
- Commissioning of Facility Starting June 1, 2014

Fluid Flow Projects

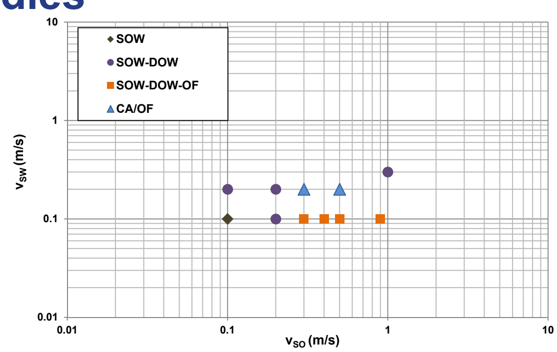
Advisory Board Meeting, September 25, 2013

Original Project

- Highly Viscous Oil-Water Flow
- Objective
  - Experimental Study of Highly Viscous Oil-Water 3-in pipe (μ_O= 180, 260 and 380 cP)
  - Effect of Inclination Angle (0,+2° and -2°)
  - Mechanistic Model Development for Highly Viscous Oil-Water Flow

Oil-Water Flow

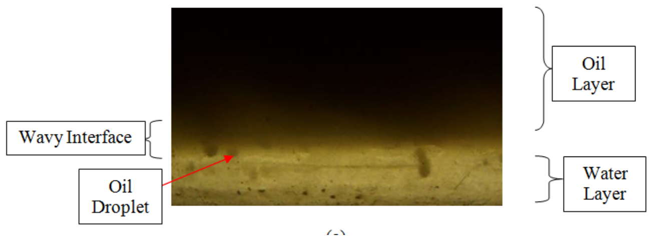
- Few Experimental Points in Previous Studies

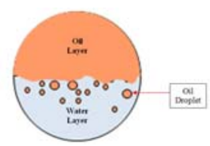


Shridhar (2011) Experimental Flow Pattern Maps for Horizontal Pipe. μo = 0.21 Pa·s.

Oil-Water Flow

- Poor Visualization for High Pressure Conditions



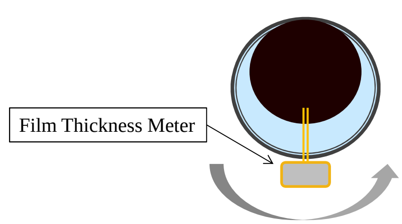


Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Oil-Water Flow

- Parameters to Be Measured
  - Flow Pattern (Better Visualization)
  - Film Thickness and Profile
  - Pressure Drop
  - Water Fraction



Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Facility Utilization

- Originally Proposed Initial Project
  - Investigation of Highly Viscous Oil-Water Flow
  - Legacy from TUHOP
- Versatile Facility
- Can be Used for Many Different Projects

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Facility Utilization …

- Potential Projects
  - Medium Viscosity Oil Studies
    - Oil and Gas
      - Diameter and Pressure Upscaling
    - Oil, Gas and Water
  - High Viscosity Oil Studies
    - Oil and Gas
    - Oil, Gas and Water
  - Onset of Liquid Accumulation
    - Pressure Up-scaling
  - Others

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Moving Forward

- Membership Input Through Questionnaire for the First Project
- Recruit a Ph.D. Student
  - Starting Spring 2014
- Complete Facility Construction

Fluid Flow Projects

Business Report

Cem Sarica

Advisory Board Meeting, September 25, 2013

Membership and Collaboration Status

- Current Membership Status
  - 2013 Membership Increases by One
    - DSME of South Korea Joins
  - 17 Industrial Members and BSEE
- Efforts Continue to Increase TUFFP Membership
  - Interest from Several Companies
    - CICERM
    - Statoil
    - Kongsberg
    - MSI Kenny
- SNU Collaboration Continues

Fluid Flow Projects   Advisory Board Meeting, September 25, 2013

Publications and Papers

- Brito, R., Pereyra, E., and Sarica, C.: "Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes," OTC 24048-MS Presented at 2013 Offshore Technology Conference, Houston, TX, May 6–9, 2013.
- Al-Safran, E., Gokcal, B., and Sarica, C.: "Analysis and Prediction of Heavy Oil Two-Phase Slug Length in Horizontal Pipelines," SPE 150572 *SPE Production and Operations Journal* August 2013.
- Al-Safran, E., Kora, C., and Sarica, C.: "Bubble Fraction in Slugs in Two-Phase High Viscosity Flow in Horizontal Pipes," 16th International Conference Multiphase Production, Cannes, France, June 12-15, 2013.
- Ersoy Gokcal, G., Al-Safran, E., Sarica, C., and Zhang, H. Q.: "A Multiphase Flow Simulator Performance Study for Three-Phase Gas/Oil/Water flow Behavior in an Undulating Pipe," 16th International Conference Multiphase Production, Cannes, France, June 12-15, 2013.

Next Advisory Board Meetings

- Tentative Schedule
  - April 8, 2014
    - TUFFP Workshop
    - Facility Tour I
    - TUPDP/TUFFP Reception
  - April 9, 2014
    - TUFFP Meeting
    - TUFFP/TUPDP Reception
  - April 10, 2014
    - TUPDP Meeting
- Venue is the University of Tulsa

Financial Report

- **Year 2013 – Update**
  - **TUFFP Industrial Account**
  - **TUFFP BSEE Account**
- **Year 2014 – Proposed**
  - **TUFFP Industrial Account**
  - **TUFFP BSEE Account**

2013 Industrial Account Summary

(Prepared September 12, 2013)

Anticipated Reserve Fund Balance on January 1, 2013				**$467,197**
Income for 2013				
	2013 Anticipated Membership Fees (17@$55,000)			**935,000**
	Facility Utilization Fee (SNU)			**55,000**
Total Budget				**$ 1,457,197**
Projected Budget/Expenditures for 2012				
		Projected Budget 10/15/12	**Revised Budget 3/13/13**	**Revised Budget**
90101 - 90103	Faculty Salaries	21,829.31	8,738.92	11,752.27
90600 - 90609	Professional Salaries	46,116.87	84,840.81	85,233.10
90700 - 90703	Staff Salaries	56,673.08	90,316.00	77,916.67
90800	Part-time/Temporary	25,000.00	25,000.00	22,400.00
91000	Student Salaries - Monthly	39,600.00	31,475.00	24,500.00
91100	Student Salaries - Hourly	15,000.00	15,000.00	5,045.80
91800	Fringe Benefits	43,616.74	66,202.47	60,288.45
92102	Fringe Benefits (Students)	3,168.00	2,518.00	1,960.00
81801	Tuition & Student Fees	40,095.00	29,916.00	29,916.00
93100	General Supplies	3,000.00	3,000.00	3,000.00
93101	Research Supplies	250,000.00	250,000.00	150,000.00
93102	Copier/Printer Supplies	500.00	500.00	500.00
93104	Computer Software	2,000.00	2,000.00	2,000.00
93106	Office Supplies	3,000.00	3,000.00	4,000.00
93150	Computers ($1000 - $4999)	10,000.00	10,000.00	10,000.00
93200	Postage and Shipping	500.00	500.00	1,500.00
93300	Printing and Duplicating	3,000.00	3,000.00	3,000.00
93400	Telecommunications	1,000.00	1,000.00	1,000.00
93500	Membership	500.00	500.00	500.00
93601	Travel - Domestic	10,000.00	10,000.00	10,000.00
93602	Travel - Foreign	10,000.00	10,000.00	10,000.00
93700	Entertainment	20,000.00	20,000.00	23,000.00
94803	Consultant	2,000.00	2,000.00	-
94813	Outside Services	40,000.00	40,000.00	125,000.00
95103	Equipment Rental	20,000.00	20,000.00	25,000.00
95200	F&A (55.6%)	107,010.89	133,814.27	122,731.71
98901	Employee Recruiting	3,000.00	3,000.00	3,000.00
99001	Equipment	300,000.00	300,000.00	120,000.00
99300	Bank Charges	40.00	40.00	20.00
Total Anticipated Expenditures		**1,076,649.89**	**1,166,361.47**	**933,264.00**
Anticipated Reserve as of 12/31/13				**523,933.33**

2013 BSEE Account Summary

(Prepared September 3, 2013)

Reserve Balance as of 12/31/13				**2,277.95**
2013 Budget				**55,000.00**
Total Budget				**57,277.95**

Projected Budget/Expenditures for 2013

		Budget	2013 Expenditures	
91000	Students - Monthly	28,125.00	21,000.00	
91202	Student Fringe Benefits	2,250.00	1,680.00	
95200	F&A	15,637.50	11,676.00	
Total Anticipated Expenditures as of 12/31/13		**46,012.50**	**34,356.00**	
Total Anticipated Reserve Fund Balance as of 12/31/13				**22,921.95**

Facility Improvements

- **Total Estimated Cost - $520,000**
  - **6" High Pressure Test Facility**
    - **$270,000**
  - **3" High Pressure Test Facility**
    - **$80,000**
  - **Instrumentation Improvements**
    - **$170,000**

6” High Pressure Test Facility

- Addition of Water Phase
  - Estimated Cost - $270,000
    - Tank - $50,000
    - Pumps (2 @ $50,000) - $100,000
    - Meters (3 @ $15,000) - $45,000
    - Labor - $50,000
      - Welding, etc.
    - Miscellaneous - $25,000

3” High Pressure Test Facility

- To Complete Facility
  - Estimated Cost - $80,000
    - Heater - $15,000
    - Generator - $45,000
    - Data Acquisition - $10,000
    - Oil - $10,000

Specialty Instrumentation

- Estimated Cost - $170,000
  - Particle Image Velocimetry (PIV)
    - $150,000
  - Hot Film Anemometer (probes)
    - $20,000

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

2014 Proposed Industrial Account Budget

(Prepared September 18, 2013)

Anticipated Reserve Fund Balance on January 1, 2014		**$523,933.33**
Income for 2014		
	2014 Membership Fees (17 @ $60,000 - excludes BSEE)	**$1,020,000.00**
	2014 Anticipated New Membership (2 @ $60,000)	**$120,000.00**
	Facility Utilization Fee (SNU)	**$60,000.00**
Total Income		**$1,723,933.33**
2009 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	60,834.11
90600-90609	Professional Salaries	188,654.78
90700-90703	Staff Salaries	84,233.33
90800	Part-time/Temporary Staff	25,000.00
91000	Graduate Students	82,200.00
91100	Undergraduate Students	15,000.00
91800	Fringe Benefits (36%)	120,140.00
92102	Fringe Benefits Students (8%)	6,576.00
81801	Tuition/Student Fees	90,492.75
93100	General Supplies	3,000.00
93101	Research Supplies	125,000.00
93102	Copier/Printer Supplies	500.00
93104	Computer Software	2,000.00
93106	Office Supplies	4,000.00
93150	Computers Under $5000	10,000.00
93200	Postage/Shipping	1,500.00
93300	Printing/Duplicating	3,000.00
93400	Telecommunications	1,000.00
93500	Memberships/Subscriptions	500.00
93601	Travel - Domestic	10,000.00
93602	Travel - Foreign	10,000.00
93700	Entertainment (Advisory Board Meetings)	25,000.00
94813	Outside Services	75,000.00
95103	Equipment Rental	20,000.00
95200	Indirect Costs (52.4%)	238,903.24
98901	Employee Recruiting	3,000.00
99001	Equipment	455,000.00
99300	Bank Charges	40.00
	Total Expenditures	**$1,660,574.20**
Anticipated Reserve Fund Balance on December 31, 2014		**$63,359.13**

2014 Proposed BSEE Account Budget

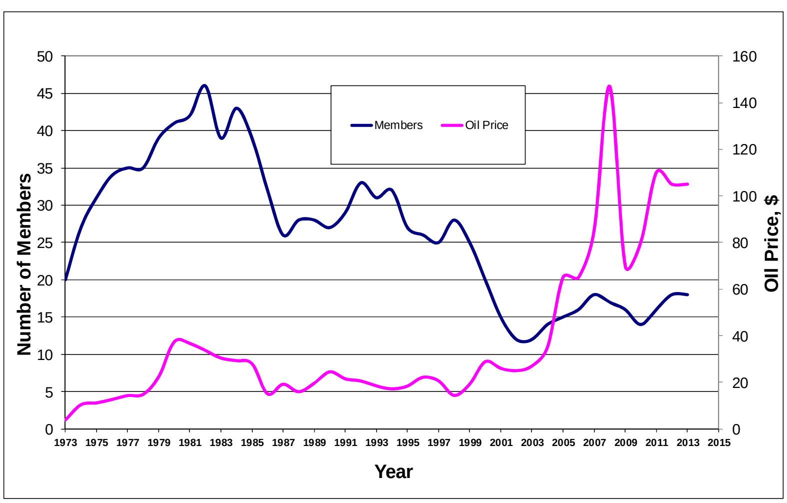
(Prepared September 3, 2013)

Account Balance - January 1, 2014		**$22,921.95**
Income for 2014		
	2014 Membership Fee	**$60,000.00**
Total Income for 2014		**$82,921.95**
2009 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	**-**
90600-90609	Professional Salaries	-
90700-90703	Staff Salaries	**-**
91000	Graduate Students	42,000.00
92102	Student Fringe Benefits (8%)	3,360.00
95200	Indirect Costs (40%)	16,800.00
	Total Expenditures	**$62,160.00**
Anticipated Reserve Fund Balance on December 31, 2014		**$20,761.95**

Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

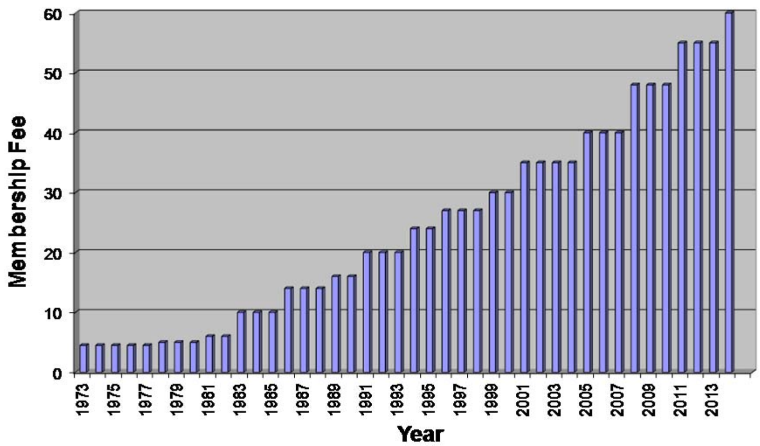
History – Membership



Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

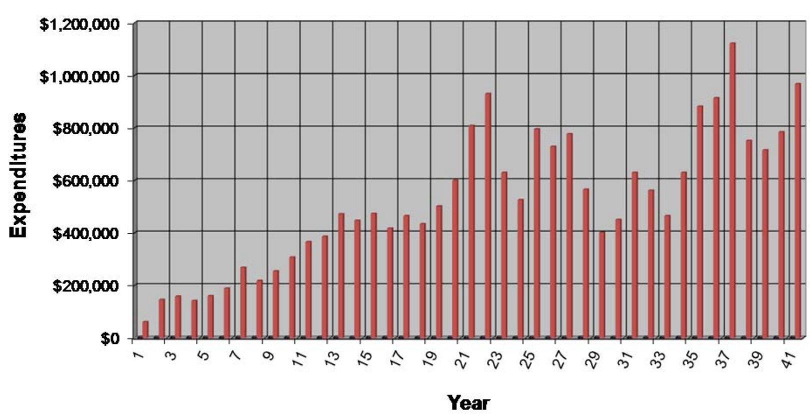
History – Membership Fees



Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

History - Expenditures



Fluid Flow Projects

Advisory Board Meeting, September 25, 2013

Membership Fees

- 2013 Membership Dues
  - 17 Paid
  - 1 Unpaid (In Process)

Introduction

This semi-annual report is submitted to Tulsa University Fluid Flow Projects (TUFFP) members to summarize activities since the April 17, 2013 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 81st semi-annual Advisory Board meeting to be held in Madrid-I of Renaissance Hotel Tulsa, OK 74133 on Wednesday, September 25, 2013.

The activities will start with the TUFFP workshop on September 24, 2013 between 12:30 p.m. and 2:00 p.m. in Madrid-I of the Renaissance Hotel. Several presentations will be made by TUFFP member companies. Between 2:00 and 3:30 pm, there will be a planning meeting for the utilization of the 6-in. High Pressure Facility. A tour of the facilities at the North Campus of the University of Tulsa will be given between 4:00 and 6:00 pm. Several facilities will be operating during the tour. Following the tour, there will be a TUFFP reception between 6:00 p.m. and 9:30 p.m. in Madrid-II of the Renaissance Hotel.

The TUFFP Advisory Board meeting will convene at 8:00 a.m. on September 25 in Madrid-I at the Renaissance Hotel Tulsa, and will adjourn at approximately 5:30 p.m. Following the meeting, there will be a joint TUFFP/TUPDP reception between 6:00 and 9:00 p.m. in Madrid-II.

The Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board meeting will be held on September 26, 2013 in Madrid I of the Renaissance Hotel between 8:30 a.m. and 2:30 p.m.

The following dates have tentatively been established for the Spring 2014 Advisory Board meetings. The venue for the Spring 2014 Advisory Board meetings is tentatively set to be at the University of Tulsa Main Campus.

2014 Spring Meetings	
April 8, 2014	Facility Tour TUFFP Workshop TUPDP/TUFFP Reception
April 9, 2014	TUFFP Advisory Board Meeting TUFFP/TUPDP Reception
April 10, 2014	TUPDP Advisory Board Meeting

Personnel

Dr. Cem Sarica, F.H. "Mick" Merelli/Cimarex Energy Professor of Petroleum Engineering, continues as the Director of TUFFP, TUPDP, and TUHWALP.

Dr. Eduardo Pereyra continues to serve as the Associate Director of TUFFP. Dr. Pereyra began serving as an Assistant Professor at the McDougall School of Petroleum Engineering in August 2013.

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

Dr. Carlos F. Torres continues as Post-Doctoral Research Associate of TUFFP and TUHWALP consortia.

Dr. Jinho Choi continues as post-doctoral research associate. He is assigned to work on model development and software improvement for both TUFFP and TUPDP.

Dr. Abdel Al-Sarkhi of King Fahd University of Petroleum and Minerals continues to serve as Research 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.

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

Mr. Norman Stegall continues as the electro-mechanical technician.

Mr. Don Harris continues as the electronic research technician. Don has been with TU for 23 years working for the College of Engineering and Natural Sciences as instrumentation technician prior to joining TUFFP.

Mr. Franklin Birt continues as the electronic research technician. Franklin worked for the Hydrates group for three years before joining our group.

Ms. Linda Jones continues as the Project Coordinator. She keeps the project accounts in addition to other responsibilities such as external communications, publishing and distributing all research reports and deliverables.

Due to our increased activities, we have upgraded Sheri Alexander's part-time Administrative Assistant position to a full-time Project Coordinator position. This position has recently been filled by Ms. Kelley Friedberg. Kelley served as the Project Coordinator of Tulsa University Artificial Lift Projects (TUALP) for over 11 years. Kelley has a BA degree in Literature and Languages from the University of Oklahoma, and she is currently pursuing an MA degree in English at the University of Tulsa. Linda and Kelley will be collectively handling all of the consortium and related project activities including the management of the project websites.

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

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

Mr. Feras Al-Ruhaimani, from Kuwait, is pursuing a Ph.D. Degree in Petroleum Engineering. Mr. Al-Ruhaimani has BS and MS degrees in Petroleum Engineering from Kuwait University. He has also worked as a petroleum engineer for Kuwait Oil Company for six years. He is studying high viscosity oil multiphase flow.

Mr. Yasser Al-Saadi, from Saudi Arabia, continues as a research assistant pursuing an MS degree in Petroleum Engineering. He has worked for Saudi Aramco as a petroleum engineer prior to starting his MS degree program at the University of Tulsa. He is studying liquid loading in highly deviated gas wells. Yasser has already been admitted to our Ph.D. program starting in the Fall 2014 semester to continue his graduate studies.

Mr. Samet Ekinci from Turkey continues as a research assistant pursuing an MS degree in Petroleum Engineering. He is fully sponsored by the Turkish Petroleum Corporation (TPAO). He is studying the effects of pipe inclination on flow characteristics of high viscosity oil-gas two-phase.

Mr. Duc Vuong rejoined the team as a Ph.D. student at the beginning of the spring 2013 semester. Duc already has BS and MS degrees from the University of Tulsa. His MS thesis work was completed under the auspices of TUHOP studying high viscosity oil and water. He has successfully passed his qualifying examinations in August 2013. Duc is assigned to the project titled "Pressure Effects on Low Liquid Loading Two-Phase Oil-Gas Flow". This project uses the new 6-in. ID. high pressure facility.

Ms. Yilin Fan, a Ph.D. student has recently joined the TUFFP team as a result of the TUHOP merger. She has been assigned to the project titled "Onset of Liquid Accumulation in Oil and Gas Pipelines." Yilin successfully passed her qualifying examinations in August 2013.

Mr. Jaejun Kim, an MS student of SNU completed his assignment in June and returned to Korea. Two new SNU students, Mr. Sunghoon Chung and Mr. Teawoo Kim recently joined TUFFP. Mr. Chung is an SNU Ph.D. student. Mr. Chung will be conducting his Ph.D. research with us. He is assigned to the project titled "Oil-Gas Flow Behavior in Downward Vertical and Highly Deviated Pipes". Mr. Kim is pursuing his MS degree at SNU. He is assigned to the "Diameter Effects on High Viscosity Oil and Gas Flow" project.

Mr. Jon Conner, a senior in petroleum engineering, joined our team as an undergraduate researcher. Jon has served in the U.S. Marine Corps for 9½ years, and has extensive experience in the oil field and general construction. He has been conducting the single-phase gas flow study in the 6-in. ID High Pressure Facility.

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

Table 1

2013 Fall Research Assistant Status

Name	Origin	Stipend	Tuition	Degree Pursued	TUFFP Project	Completion Date
Al-Ruhaimani, Feras	Kuwait	Kuwait University	Kuwait University	Ph.D. PE	Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Pipes	Fall 2014
Al-Saadi, Yasser	Saudi Arabia	Saudi Aramco	Saudi Aramco	MS – PE	Liquid Loading in Highly Deviated Gas Wells	Fall 2013
Chung, Sunghoon	South Korea	SNU	SNU	Ph.D. – PE	Effect of High Oil Viscosity on Oil-Gas Flow Behavior in Vertical Downward Pipes	Spring 2015
Ekinci, Samet	Turkey	TPC	TPC	MS – PE	Effect of Pipe Inclination on Flow Characteristics of High Viscosity Oil-Gas Two-Phase	Fall 2014
Fan, Yilin	PRC	TUHOP	TUHOP	Ph.D. – PE	Onset of Liquid Accumulation in Oil and Gas Pipelines	Spring 2016
Karami, Hamid	Iran	Yes BSEE	No Waived	Ph.D. – PE	Effects of MEG on Multiphase Flow	Fall 2014
Kim, Teawoo	South Korea	SNU	SNU	MS (SNU)	High Viscosity Oil Multiphase Flow	Summer 2014
Voung, Duc	Vietnam	TUFFP	TUFFP	Ph.D. – PE	Pressure Effects on Low Liquid Loading Two-Phase Oil-Gas Flow	Fall 2016

Membership

The current membership of TUFFP is up from 17 to 18 for 2013: 17 industrial members and the Bureau of Safety and Environmental Enforcement (BSEE). We have gained DSME of South Korea as the newest TUFFP member. Our efforts to increase the TUFFP membership level will continue. The paperwork for the membership of CICERM is underway. Statoil indicated their desire to join TUFFP. Kongsberg notified us that they would like to join TUFFP in 2014. Recently, MSIKenny showed interest in TUFFP.

Table 2 lists all the current 2013 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 has been extended until 2015. Through this collaboration TUFFP receives about $60,000/year and visiting research scholars.

Table 2

2013 Fluid Flow Projects Membership

Aspen Tech

Baker Atlas

BSEE

BP Exploration

Chevron

ConocoPhillips

DSME

Exxon Mobil

GE

KOC

Marathon Oil Company

NTP Truboprovod Piping Systems Research & Engineering

PEMEX

Petrobras

Saudi Aramco

Schlumberger

Shell Global Solutions

Total

Equipment and Facilities Status

Test Facilities

The 6-in. ID High Pressure Facility has already been commissioned. The Canty Visualization Device has been tested. A high pressure wire mesh device has been ordered to be custom built. Visualization and wire mesh devices as well as an iso-kinetic probe device will be installed on the facility this fall.

Construction of 3-in. high pressure facility, originally started as part of the TUHOP JIP, is underway and expected to be completed by the end of 2013.

The three-phase 2-in. ID facility test section modifications to study high viscosity oil multiphase flow in vertical and deviated pipe studies have been completed.

The two-phase 2-in. ID high viscosity oil facility is brought to inclined configuration for inclined flow studies.

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

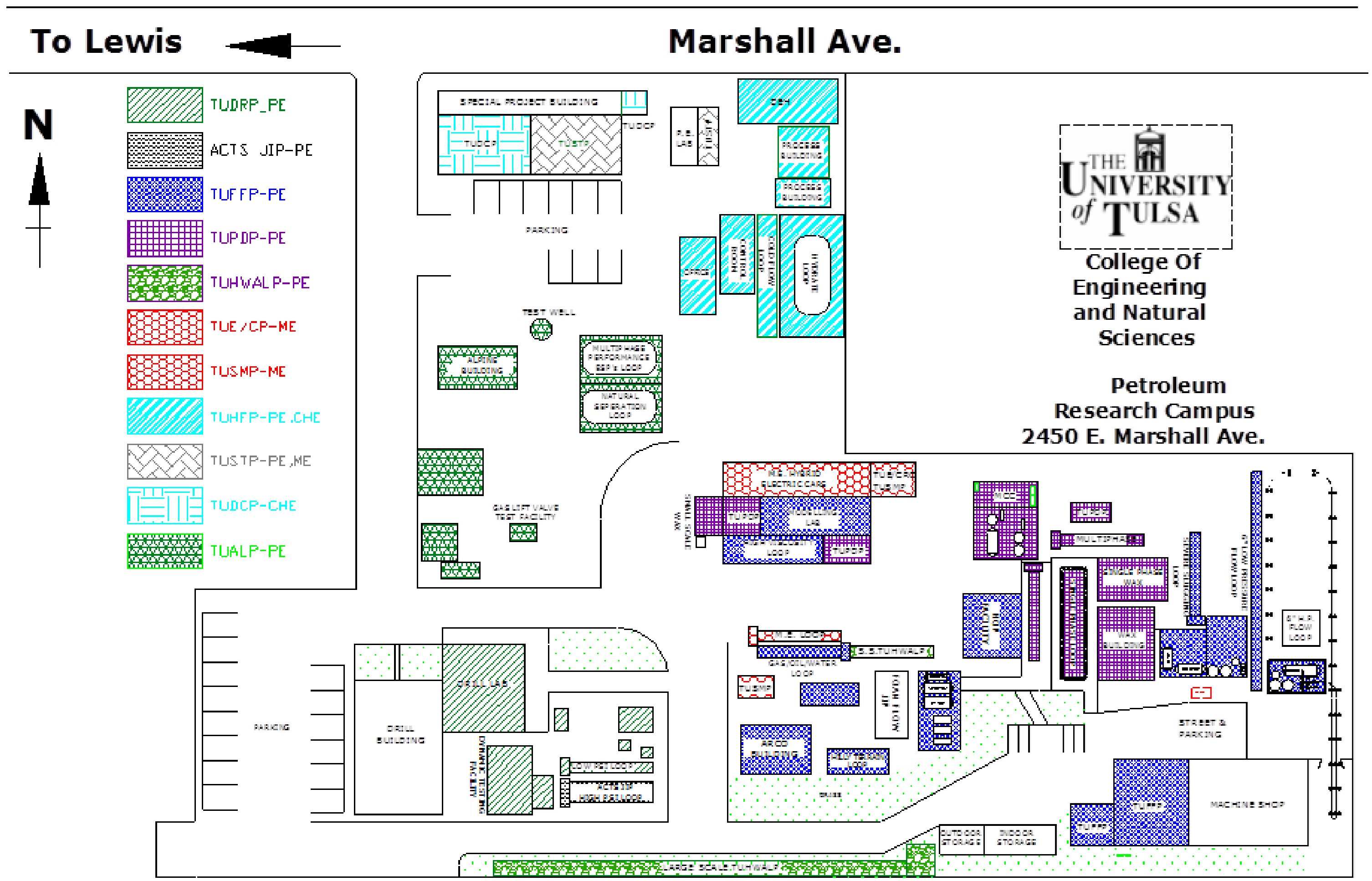


Figure 1: Site Plan for the North Campus Research Facilities

Financial Status

The TUFFP membership fee has historically been increased every three years to compensate for inflation and increases in student/staff compensation and tuition, which typically outpaces the inflation calculated from Consumer Price Index (CPI). 2013 is the last year of the current three-year cycle. Based on CPI calculations, the 2014 membership fee is set to be $60,000.

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

Table 3 presents a financial analysis of income and expenditures for the 2013 Industrial member account as of September 18, 2013. Also shown are previous 2013 budgets that have been reported to the members. The total industry expenditures for 2013 are projected to be $933,264 resulting in a carryover of $523,933 to the 2014 fiscal year.

Table 4 presents a financial analysis of expenditures and income for the BSEE Account for 2013. This account is used primarily for graduate student stipends. The total expenditures for 2013 are $34,356. A balance of $22,922 is projected to carry over into 2014. The University of Tulsa waives up to 19 hours of tuition for each graduate student that is paid a stipend from BSEE funds.

Tables 5 and 6 present the proposed budgets and projected income for the Industrial and BSEE accounts for 2014. The 2014 TUFFP industrial budget is based on 19 members. This provides $1,140,000.00 of industrial membership income for 2014. In addition, TUFFP will receive a facility utilization fee of $60,000 from SNU. The total of the 2013 income and the reserve account is projected to be $1,723,933. The expenses for the industrial member account are projected to be $1,660,574 leaving a carryover balance of $63,359 to 2015. The BSEE account is expected to have $62,160 in expenditures and a carryover of $20,762 to 2015.

Table 3: 2013 Industrial Budget Summary

(Prepared September 12, 2013)

Anticipated Reserve Fund Balance on January 1, 2013				**$467,197**
Income for 2013				
	2013 Anticipated Membership Fees (17@$55,000)			**935,000**
	Facility Utilization Fee (SNU)			**55,000**
Total Budget				**$ 1,457,197**

Projected Budget/Expenditures for 2012

		Projected Budget 10/15/12	Revised Budget 3/13/13	Revised Budget
90101 - 90103	Faculty Salaries	21,829.31	8,738.92	11,752.27
90600 - 90609	Professional Salaries	46,116.87	84,840.81	85,233.10
90700 - 90703	Staff Salaries	56,673.08	90,316.00	77,916.67
90800	Part-time/Temporary	25,000.00	25,000.00	22,400.00
91000	Student Salaries - Monthly	39,600.00	31,475.00	24,500.00
91100	Student Salaries - Hourly	15,000.00	15,000.00	5,045.80
91800	Fringe Benefits	43,616.74	66,202.47	60,288.45
92102	Fringe Benefits (Students)	3,168.00	2,518.00	1,960.00
81801	Tuition & Student Fees	40,095.00	29,916.00	29,916.00
93100	General Supplies	3,000.00	3,000.00	3,000.00
93101	Research Supplies	250,000.00	250,000.00	150,000.00
93102	Copier/Printer Supplies	500.00	500.00	500.00
93104	Computer Software	2,000.00	2,000.00	2,000.00
93106	Office Supplies	3,000.00	3,000.00	4,000.00
93150	Computers ($1000 - $4999)	10,000.00	10,000.00	10,000.00
93200	Postage and Shipping	500.00	500.00	1,500.00
93300	Printing and Duplicating	3,000.00	3,000.00	3,000.00
93400	Telecommunications	1,000.00	1,000.00	1,000.00
93500	Membership	500.00	500.00	500.00
93601	Travel - Domestic	10,000.00	10,000.00	10,000.00
93602	Travel - Foreign	10,000.00	10,000.00	10,000.00
93700	Entertainment	20,000.00	20,000.00	23,000.00
94803	Consultant	2,000.00	2,000.00	-
94813	Outside Services	40,000.00	40,000.00	125,000.00
95103	Equipment Rental	20,000.00	20,000.00	25,000.00
95200	F&A (55.6%)	107,010.89	133,814.27	122,731.71
98901	Employee Recruiting	3,000.00	3,000.00	3,000.00
99001	Equipment	300,000.00	300,000.00	120,000.00
99300	Bank Charges	40.00	40.00	20.00
Total Anticipated Expenditures		**1,076,649.89**	**1,166,361.47**	**933,264.00**
Anticipated Reserve as of 12/31/13				**523,933.33**

Table 4: 2013 BSEE Budget Summary

(Prepared September 3, 2013)

Reserve Balance as of 12/31/13			**2,277.95**
2013 Budget			**55,000.00**
Total Budget			**57,277.95**

Projected Budget/Expenditures for 2013

	Budget	**2013 Expenditures**	
91000 Students - Monthly	28,125.00	21,000.00	
91202 Student Fringe Benefits	2,250.00	1,680.00	
95200 F&A	15,637.50	11,676.00	
Total Anticipated Expenditures as of 12/31/13	**46,012.50**	**34,356.00**	
Total Anticipated Reserve Fund Balance as of 12/31/13			**22,921.95**

Table 5: Proposed 2014 Industrial Budget

(Prepared September 18, 2013)

Anticipated Reserve Fund Balance on January 1, 2014		**$523,933.33**
Income for 2014		
	2014 Membership Fees (17 @ $60,000 - excludes BSEE)	**$1,020,000.00**
	2014 Anticipated New Membership (2 @ $60,000)	**$120,000.00**
	Facility Utilization Fee (SNU)	**$60,000.00**
Total Income		**$1,723,933.33**
2009 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	60,834.11
90600-90609	Professional Salaries	188,654.78
90700-90703	Staff Salaries	84,233.33
90800	Part-time/Temporary Staff	25,000.00
91000	Graduate Students	82,200.00
91100	Undergraduate Students	15,000.00
91800	Fringe Benefits (36%)	120,140.00
92102	Fringe Benefits Students (8%)	6,576.00
81801	Tuition/Student Fees	90,492.75
93100	General Supplies	3,000.00
93101	Research Supplies	125,000.00
93102	Copier/Printer Supplies	500.00
93104	Computer Software	2,000.00
93106	Office Supplies	4,000.00
93150	Computers Under $5000	10,000.00
93200	Postage/Shipping	1,500.00
93300	Printing/Duplicating	3,000.00
93400	Telecommunications	1,000.00
93500	Memberships/Subscriptions	500.00
93601	Travel - Domestic	10,000.00
93602	Travel - Foreign	10,000.00
93700	Entertainment (Advisory Board Meetings)	25,000.00
94813	Outside Services	75,000.00
95103	Equipment Rental	20,000.00
95200	Indirect Costs (52.4%)	238,903.24
98901	Employee Recruiting	3,000.00
99001	Equipment	455,000.00
99300	Bank Charges	40.00
	Total Expenditures	**$1,660,574.20**
Anticipated Reserve Fund Balance on December 31, 2014		**$63,359.13**

Table 6: Proposed 2014 BSEE Budget

(Prepared September 3, 2013)

Account Balance - January 1, 2014		**$22,921.95**
Income for 2014		
	2014 Membership Fee	**$60,000.00**
Total Income for 2014		**$82,921.95**
2009 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	-
90600-90609	Professional Salaries	-
90700-90703	Staff Salaries	-
91000	Graduate Students	42,000.00
92102	Student Fringe Benefits (8%)	3,360.00
95200	Indirect Costs (40%)	16,800.00
	Total Expenditures	**$62,160.00**
Anticipated Reserve Fund Balance on December 31, 2014		**$20,761.95**

Miscellaneous Information

Fluid Flow Projects Short Course

The 39th TUFFP "Two-Phase Flow in Pipes" short course is scheduled for May 12 – 16, 2014. We encourage early enrollment, if possible.

Ph.D. Students Pass Their Qualifying Exams

Two TUFFP and one TUHWALP students successfully passed their Ph.D. This is a rite of passage for Ph.D. students. We congratulate Ms. Rosmer Brito, Ms. Yilin Fan and Mr. Duc Vuong.

Abdel Al-Sarkhi Spends Summer with TUFFP Researchers

Once again, Dr. Abdel Al-Sarkhi spent a productive three months with TUFFP during the summer of 2013. He helped TUFFP graduate students and worked on the application minimum and equal energy dissipation concepts to multiphase flow.

Eduardo Pereyra Joins Petroleum Engineering Faculty

Dr. Eduardo Pereyra, Associate Director of TUFFP, has joined the McDougall School of Petroleum Engineering as a Tenure-Track Assistant Professor, effective Fallall 2013 semester.

Cem Sarica Becomes "Mick" Merelli / Cimarex Energy Professor of Petroleum Engineering

Denver-based Cimarex Energy Co. invested $3.5 million to further advance The University of Tulsa's College of Engineering and Natural Sciences.

Cimarex's gift in the amount of $2.5 million established a permanent tribute to the legacy of its founder, F.H. "Mick" Merelli, by endowing a faculty chair in TU's renowned McDougall School of Petroleum Engineering. The newly established F.H. "Mick" Merelli/Cimarex Energy Chair assists in recruiting and retaining distinguished faculty; the first holder of the chair will be Dr. Cem Sarica, professor of petroleum engineering.

The remaining $1 million of the Cimarex investment established a TU Trustee scholarship fund for deserving students in the petroleum engineering program.

TUFFP Journal Article Makes Top 25

The article titled *"Modeling of droplet entrainment in co-current annular two-phase flow: A new approach"* is recognized by ScienceDirect as one of the Top 25 papers published in the International Journal of Multiphase Flow in 2012.

BHR Group Conference on Multiphase Technology

Since 1991, TUFFP has participated as a co-supporter of the 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 events providing delegates with opportunities to discuss new research and developments, to consider innovative solutions in the multiphase production area.

The 9th North American Conference on Multiphase Technology sponsored by FMC Technologies, Bornemann Pumps, Kongsberg, and LiquidPower, and supported by TUFFP, will be held 11-13 of June 2014 in Banff, Canada. This 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, consulting and technology companies. The conference brings together experts from across the American continents and worldwide. Detailed information about the conference can be found in BHRg's (www.brhgroup.com).

The BHRg multiphase flow conferences have been an excellent venue in the areas of multiphase flow and flow assurance. We recommend both the Cannes and Banff meetings to our members. We also encourage active participation by submitting paper abstracts. The abstract deadline is Nov. 25, 2013.

Publications & Presentations

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

1) Brito, R., Pereyra, E., and Sarica, C.: "Effect of Medium Oil Viscosity on Two-Phase Oil-Gas

Flow Behavior in Horizontal Pipes," OTC 13OTC-P-866-OTC Presented at 2013 Offshore Technology Conference, Houston, TX, May 6–9, 2013.

2) Al-Safran, E., Gokcal, B., and Sarica, C.: "Analysis and Prediction of Heavy Oil Two-Phase Slug Length in Horizontal Pipelines," SPE 150572 *SPE Production and Operations Journal* August 2013.
3) Al-Safran, E., Kora, C., and Sarica, C.: "Bubble Fraction in Slugs in Two-Phase High Viscosity Flow in Horizontal Pipes," 16th International Conference Multiphase Production, Cannes, France, June 12-15, 2013.
4) Ersoy Gokcal, G., Al-Safran, E., Sarica, C., and Zhang, H. Q.: "A Multiphase Flow Simulator Performance Study for Three-Phase Gas/Oil/Water Flow Behavior in an Undulating Pipe," 16th International Conference Multiphase Production, Cannes, France, June 12-15, 2013.

Tulsa University Paraffin Deposition Projects (TUPDP)

The fifth three-year phase has been started effective April 1, 2013. The new phase studies concentrate on the paraffin deposition characterization of single-phase turbulent flow with new oils, gas-oil-water paraffin deposition, and field verification. TUPDP currently has 7 members. The membership fee is $65,000/year.

Tulsa University Horizontal Well Artificial Lift Projects (TUHWALP)

The TUHWALP consortium was founded on July 1, 2012. TUHWALP primarily addresses the artificial lift needs of horizontal wells drilled into gas and oil shales. Currently, TUHWALP has 16 members. The membership fee is $50,000/year.

TUHWALP's mission is to:

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

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

This JIP investigates unloading of vertical gas wells using surfactants. The JIP is funded by the Research Partnership to Secure Energy for America (RPSEA), which is an organization managing DOE funds, and various oil and gas operating and service companies. Currently, there are 6 industrial members.

Appendix A

Personnel Contact Information

Director

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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 R: 2012 **Current**
3.	Getty Oil Co.	19 Jun. '72	T: 11 Oct. '84 with sale to Texaco
4.	Union Oil Co. of California	7 Jul. '72	T: for 2001
5.	Intevep	3 Aug. '72	TR: from CVP in '77; T: 21 Jan '05 for 2006
6.	Marathon Oil Co.	3 Aug. '72	T: 17 May '85 R: 25 June '90 T: 14 Sept. '94 R: 3 June '97 **Current**
7.	Arco Oil and Gas Co.	7 Aug. '72	T: 08 Dec. '97
8.	AGIP	6 Sep. '72	T: 18 Dec. '74
9.	Otis Engineering Corp.	4 Oct. '72	T: 15 Oct. '82
10.	ConocoPhillips, Inc.	5 Oct. '72	T: Aug. '85 R: 5 Dec. '86 **Current**
11.	Mobil Research and Development Corp.	13 Oct. '72	T: 27 Sep. 2000
12.	Camco, Inc.	23 Oct. '72	T: 15 Jan. '76 R: 14 Mar. '79 T: 5 Jan. '84
13.	Crest Engineering, Inc.	27 Oct. '72	T: 14 Nov. '78 R: 19 Nov. '79 T: 1 Jun. '84
14.	Chevron	3 Nov. '72	**Current**
15.	Aminoil	9 Nov. '72	T: 1 Feb. '77

16.	Compagnie Francaise des Petroles (TOTAL)	6 Dec. '72	T: 22 Mar. '85 R: 23 Oct. '90 T: 18 Sep. '01 for 2002 R: 18 Nov. '02 **Current**
17.	Oil Service Co. of Iran	19 Dec. '72	T: 20 Dec. '79
18.	Sun Exploration and Production Co.	4 Jan. '73	T: 25 Oct. '79 R: 13 Apr. '82 T: 6 Sep. '85
19.	Amoco Production Co. (now as BP Amoco)	18 May '73	
20.	Williams Brothers Engrg. Co.	25 May '73	T: 24 Jan. '83
		1974	
21.	Gulf Research and Development Co.	20 Nov. '73	T: Nov. '84 with sale to Chevron
22.	El Paso Natural Gas Co.	17 Dec. '73	T: 28 Oct. '77
23.	Arabian Gulf Exploration Co.	27 Mar. '74	T: 24 Oct. '82
24.	ExxonMobil Upstream Research	27 Mar. '74	T: 16 Sep. '86 R: 1 Jan. '88 T: 27 Sep. 2000 R: 2007 **Current**
25.	Bechtel, Inc.	29 May '74	T: 14 Dec. '76 R: 7 Dec. '78 T: 17 Dec. '84
26.	Saudi Arabian Oil Co.	11 Jun. '74	T: for 1999 R: for 2003 T: for 2007 R: for 2012 **Current**
27.	Petrobras	6 Aug. '74	T: for 2000 R: for 2005 **Current**
		1975	
28.	ELF Exploration Production (now as TotalFina Elf)	24 Jul. '74	T: 24 Feb. '76 Tr. from Aquitaine Co. of Canada 19 Mar. '81 T: 29 Jan. '87 R: 17 Dec. '91
29.	Cities Service Oil and Gas Corp.	21 Oct. '74	T: 25 Oct. '82 R: 27 Jun. '84

			T: 22 Sep. '86
30.	Texas Eastern Transmission Corp.	19 Nov. '74	T: 23 Aug. '82
31.	Aquitaine Co. of Canada, Ltd.	12 Dec. '74	T: 6 Nov. '80
32.	Texas Gas Transmission Corp.	4 Mar. '75	T: 7 Dec. '89
	1976		
33.	Panhandle Eastern Pipe Line Co.	15 Oct. '75	T: 7 Aug. '85
34.	Phillips Petroleum Co.	10 May '76	T: Aug. 94 R: Mar 98 T: 2002
	1977		
35.	N. V. Nederlandse Gasunie	11 Aug. '76	T: 26 Aug. '85
36.	Columbia Gas System Service Corp.	6 Oct. '76	T: 15 Oct. '85
37.	Consumers Power Co.	11 Apr. '77	T: 14 Dec. '83
38.	ANR Pipeline Co.	13 Apr. '77	TR: from Michigan- Wisconsin Pipeline Co. in 1984 T: 26 Sep. '84
39.	Scientific Software-Intercomp	28 Apr. '77	TR: to Kaneb from Intercomp 16 Nov. '77 TR: to SSI in June '83 T: 23 Sep. '86
40.	Flopetrol/Johnston-Schlumberger	5 May '77	T: 8 Aug. '86
	1978		
41.	Norsk Hydro a.s	13 Dec. '77	T: 5 Nov. '82 R: 1 Aug. '84 T: 8 May ‘96
42.	Dresser Industries Inc.	7 Jun. '78	T: 5 Nov. '82
	1979		
43.	Sohio Petroleum Co.	17 Nov. '78	T: 1 Oct. '86
44.	Esso Standard Libya	27 Nov. '78	T: 2 Jun. '82
45.	Shell Internationale Petroleum MIJ B.V. (SIPM)	30 Jan. '79	T: Sept. 98 for 1999
	1980		
46.	Fluor Ocean Services, Inc.	23 Oct. '79	T: 16 Sep. '82
47.	Texaco	30 Apr. '80	T: 20 Sep. ’01 for 2002

48.	BG Technology (Advantica)	15 Sep. '80	T: 2003
	1981		
49.	Det Norske Veritas	15 Aug. '80	T: 16 Nov. '82
	1982		
50.	Arabian Oil Co. Ltd.	11 May '82	T: Oct.'01 for 2002
51.	Petro Canada	25 May '82	T:28 Oct. '86
52.	Chiyoda	3 Jun. '82	T: 4 Apr '94
53.	BP	7 Oct. '81	**Current**
	1983		
54.	Pertamina	10 Jan. '83	T: for 2000 R: March 2006
	1984		
55.	Nippon Kokan K. K.	28 Jun. '83	T: 5 Sept. '94
56.	Britoil	20 Sep. '83	T: 1 Oct. '88
57.	TransCanada Pipelines	17 Nov. '83	T:30 Sep. '85
58.	Natural Gas Pipeline Co. of America (Midcon Corp.)	13 Feb. '84	T:16 Sep. '87
59.	JGC Corp.	12 Mar. '84	T: 22 Aug. '94
	1985		
60.	STATOIL	23 Oct. '85	T:16 Mar. '89
	1986		
61.	JOGMEC (formerly Japan National Oil Corp.)	3 Oct. '86	T: 2003 R: 2007 T: 5 Sept '12
	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 Hughes	Dec. 97	**Current**
72.	Bureau of Safety and Environmental Enforcement (BSEE)	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		T: 2013 (Merger)
	2011		
82.	General Electric		**Current**
83.	Aspen Technology, Inc.		**Current**
	2013		
84.	Piping Systems Research & Engineering Co. (NTP Truboprovod)		**Current**

85.	DSME	19 June ‘13	**Current**

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

Appendix D

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 <u>CORE</u> 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).

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