THE UNIVERSITY of TULSA

Department of Petroleum Engineering

Fluid Flow Projects

Seventieth Semi-Annual Advisory Board Meeting Brochure and Presentation Slide Copy

April 15, 2008

Tulsa University Fluid Flow Projects
Seventieth Semi-Annual Advisory Board Meeting Agenda
Tuesday, April 15, 2008

Monday
April 14, 2008

Tulsa University High-Viscosity Oil Projects
Advisory Board Meeting
University of Tulsa – Allen Chapman Activity Center (ACAC) – Gallery
440 South Gary Street
Tulsa, Oklahoma
8:00 – 11:45 a.m.

Tulsa University High-Viscosity Oil Projects and Tulsa University Fluid Flow Projects Workshop Luncheon
University of Tulsa – Allen Chapman Activity Center (ACAC) – Chouteau C
440 South Gary Street
Tulsa, Oklahoma
11:45 – 1:00 p.m.

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

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

Tulsa University High-Viscosity Oil Projects and Tulsa University Fluid Flow Projects
Reception
University of Tulsa – Reynolds Center – President's Suite
3208 East 8th Street
Tulsa, Oklahoma
6:00 – 9:00 p.m.

Tuesday
April 15, 2008

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Wednesday
April 16, 2008

Tulsa University Paraffin Deposition Projects
Advisory Board Meeting
University of Tulsa – Allen Chapman Activity Center (ACAC) – Gallery
440 South Gary Street
Tulsa, Oklahoma
8:00 a.m. – 3:00 p.m.

Tulsa University Fluid Flow Projects
Seventieth Semi-Annual Advisory Board Meeting Agenda
Tuesday, April 15, 2008

8:00 a.m.	**Breakfast** **Allen Chapman Activity Center - Gallery**	
8:30	**Introductory Remarks**	Cem Sarica
	Executive Summary	Cem Sarica
9:00	**TUFFP Progress Reports**	
	An Experimental and Theoretical Investigation of Slug Flow for High Oil Viscosity in Horizontal and Near-Horizontal Pipes	Bahadir Gokcal
	Liquid Entrainment in Annular Two-Phase Flow in Inclined Pipes	Kyle Magrini
10:25	**Coffee Break**	
10:40	**TUFFP Progress Reports**	
	Low Liquid Loading Gas-Oil-Water Flow in Horizontal Pipes – Research Overview	Abdel Al-Sarkhi
	Low Liquid Loading Gas-Oil-Water Flow in Near Horizontal Pipes	Feng Xiao
	Three Phase Flow Unified Model Update	Holden Zhang
12:00 p.m.	**Lunch – President's Formal Lounge**	
1:00 p.m.	**TUFFP Progress Reports**	
	New High Viscosity Modeling	Holden Zhang
	Investigation of Three-Phase Gas-Oil-Water Flow in Hilly-Terrain Pipelines	Gizem Ersoy
	A Study on Oil-Water Flow Closure Relationships	Anoop Sharma
2:15	**Coffee Break**	
2:30	**TUFFP Project Reports**	
	Up-scaling Studies in Multiphase Flow	Abdel Al-Sarkhi
	Lagrangian-Eulerian Transient Two-phase Flow Model	Kwon Il Choi
	Modeling of Gas-Liquid Flow in an Upward Vertical Annulus	Tingting Yu
3:45	**TUFFP Business Report**	Cem Sarica
4:00	**Open Discussion**	Cem Sarica
4:30	**Adjourn**	
6:00	**TUFFP/TUPDP Reception** **Reynolds Center – President's Suite**	

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TUFFP Business Report

Appendices

Executive Summary

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

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

- *"Characterization of Oil-water Two-phase Flow in Horizontal and Slightly Inclined Pipes"*. Our three-phase model requires knowledge on oil/water interaction. Moreover, oil-water flow is of interest for many applications ranging from horizontal well flow to separator design. The objectives of this study are to assess performance of current models by checking them against experimental data and improve the models through better closure relationships. High speed video and other instruments are being utilized to gather detailed information such as drop size distribution as a function of flow patterns.

  After the studies by Vielma Atmaca on horizontal and inclined oil-water flow studies,, Sharma is now focusing on closure relationship development that will be incorporated in the TUFFP unified three-phase model. Based on Atmaca's oil-water data, Sharma has observed that the highest viscosity does not correspond to the inversion point of oil-water dispersions under pipe flow conditions. Observations indicated that the highest mixture viscosity occurs at very low water-cut values. This has significant importance with respect to modeling of both oil-water and gas-oil-water flows. Sharma will attempt to model this behavior.

- *"High Viscosity Oil Two-phase Flow Behavior"*. Oils with viscosities as high as 10,000 cp are produced from many fields around the world. Current multiphase flow models are largely based on experimental data with low viscosity fluids. The gap between lab and field data may be three orders of magnitude or more. Therefore, current mechanistic models need to be verified with higher liquid viscosity experimental results. Modifications or new developments are necessary.

  Almost all flow models have viscosity as an intrinsic variable. Multiphase flow is expected to exhibit significantly different behavior for higher viscosity oils. Many flow behaviors will be affected by liquid viscosity, including droplet formation, surface waves, bubble entrainment, slug mixing zone, and even three-phase stratified flow.

  An earlier TUFFP study conducted by Gokcal showed that the performances of existing models are not sufficiently accurate for high viscosity oils. It was found that increasing oil viscosity had a significant effect on flow behavior. Mostly, intermittent flow (slug and elongated bubble) was observed in his study. Based on his results, this study will initially focus on the slug flow region.

  Air and highly viscous oil two-phase experiments will be performed with the 2-in. ID high viscosity indoor facility. Pressure drop and slug characteristics, including translational velocity, slug liquid holdup, slug length and frequency, will be measured in this study. Drift velocity measurements for a horizontal pipe configuration made last fall indicated that the drift velocity decreases with increasing liquid viscosity. Since the last Advisory Board meeting, the drift velocity measurements were completed for the entire range of upward inclination angles for a viscosity range of 200 – 1200 cp. Moreover a drift flux model for a horizontal configuration was developed. Model predictions matched the experimental data well. After the Advisory Board meeting, the model will be extended to inclined configurations and experimental studies will focus on translational velocity and slug lengths.

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

  Currently, our efforts in droplet homo-phase interaction are underway in oil-water flow, high viscosity oil two-phase flow and low-liquid loading projects.

  A past sensitivity study of multiphase flow predictive models showed that, in stratified and annular flow, the variation of droplet entrainment fraction can significantly affect the predicted pressure gradient. Although better entrainment fraction correlations were proposed, a need was identified to experimentally investigate entrainment fraction for inclined pipes. A new experimental study was initiated to further investigate entrainment fraction for various inclination angles. The 3-in. ID severe slugging facility will be utilized for this project. A new device to measure entrainment fraction has been developed and a prototype for 2-in. ID pipe has been tested in the gas-oil-water facility. The design has been improved based on the test results.

- *"Lagrangian-Eulerian Transient Two-Phase Model"*. The main motivation for this study comes from the need to mitigate hydrate formation following cool-down of fluids and high pressure surge during shut-in. A study of the transient temperature variation along with phase redistribution is critical for the design of a flow line-riser system as well as for flow assurance during production cycle.

  A two-phase transient model was first formulated and solved. The model is capable of simulating phase redistribution. Currently, efforts are made to expand the approach to other transients and implementation of three-phase.

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

  During the last Advisory Board meeting, results of the first horizontal flow testing were presented. A large amount of data was collected on various flow parameters such as flow patterns, phase distribution, onset of droplet entrainment, entrainment fraction, and film velocity. The results revealed a new flow phenomenon.

  Since the last Advisory Board meeting, a new graduate student has studied various aspects of low liquid loading. He will be studying low liquid loading for inclined pipe configurations.

- *"Multiphase Flow in Hilly Terrain Pipelines"*. Three-phase flow in hilly terrain pipelines is a common occurrence. The existence of a water phase in the system poses many potential flow assurance and processing problems. Most of the problems are directly related to the flow characteristics. Although the characteristics of two-phase gas-liquid flow have been investigated extensively, there are very few studies addressing multiphase gas-oil-water flow in hilly terrain pipelines. The general objectives of this project are to thoroughly investigate and compare existing models, and develop closure relationships and predictive models for three-phase flow of gas-oil-water in hilly-terrain pipelines.

  Originally, use of the TUFFP's 1400-ft long pipeline was planned for this study. Due to extensive modifications required, the three-phase gas-oil-water flow facility was decided to be used with the approval of the Advisory Board at the fall 2007 meeting. Since the Fall AB meeting, design of the modifications to the facility has been completed and implementation is currently underway.

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

  A detailed drawing of the facility has now been prepared and the location of the facility was identified. Major equipment such as a circulation compressor, heat exchanger, three-phase separator, liquid tanks and a generator have been sized and identified. Among these, the generator has already been purchased. The longest lead time item, the gas compressor, has been ordered and is expected to be received during the Fall of 2008. Currently, efforts are focused on design modifications for a safe and compliant operation of the facility.

- "*Unified Mechanistic Model*". TUFFP maintains, and continuously improves upon the TUFFP unified model. Current efforts are concentrated on improving the robustness of the unified model computer programs. After the completion of modifications, the unified model will be an easy plug-in to commercial simulators. We are collaborating with Schlumberger on Unified Model Program improvements. The results of the collaborative efforts will be at this AB meeting.

- A new project on multiphase flow in an annulus has beeb initiated. TUFFP has not conducted any study on this topic since Caetano's pioneering work in 1985. There were several members requesting us to improve our annulus flow model. Tingting Yu, a Teaching Assistant of petroleum engineering, has been assigned to this project. Yu is mostly funded by the petroleum engineering department. She will be revisiting the annulus flow modeling in light of new developments in regular pipe flow mechanistic models. Caetano's data will be utilized in this project.

Since the last Advisory Board meeting, Landmark has terminated their membership. Therefore, current TUFFP membership stands at 17 (16 industrial companies and MMS). DOE supports TUFFP in the development of new generation multiphase flow predictive tools for three-phase flow research. DOE's support translates into the equivalent of four additional members for five years, effective July 2003. Efforts continue to further increase the TUFFP membership level. A detailed financial report is provided in this report. We thank our members for their continued support.

Several related projects are underway. The related projects involve sharing of facilities and personnel with TUFFP. The Paraffin Deposition consortium, TUPDP, is into its third phase with 11 members. The Center of Research Excellence (TUCoRE) initiated by Chevron at The University of Tulsa funds several research projects. TUCoRE activities in the area of Heavy Oil Multiphase Flow have resulted in a new Joint Industry Project (JIP) to investigate Heavy Oil Multiphase Flow in more detail. The JIP currently has three members. Chevron has already made $380,000 commitment to upgrade an existing facility to be used in the project.

Fluid Flow Projects

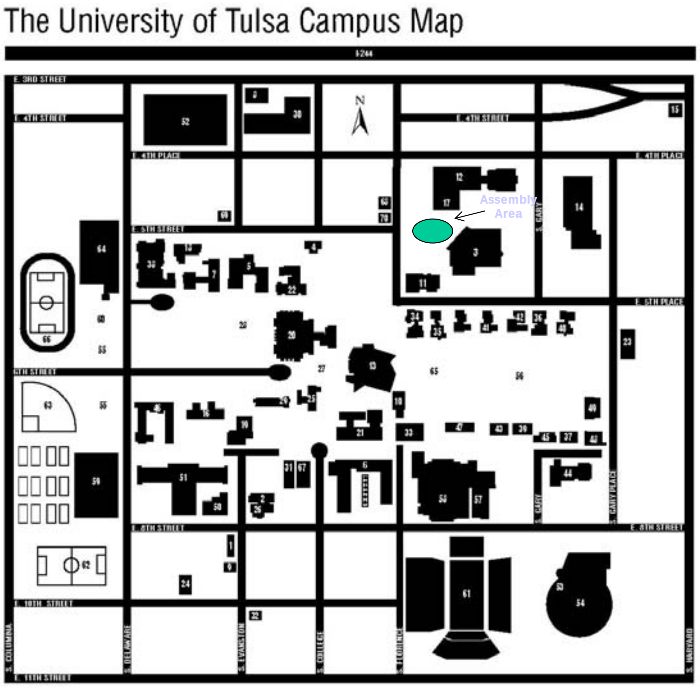
70th Fluid Flow Projects Advisory Board Meeting

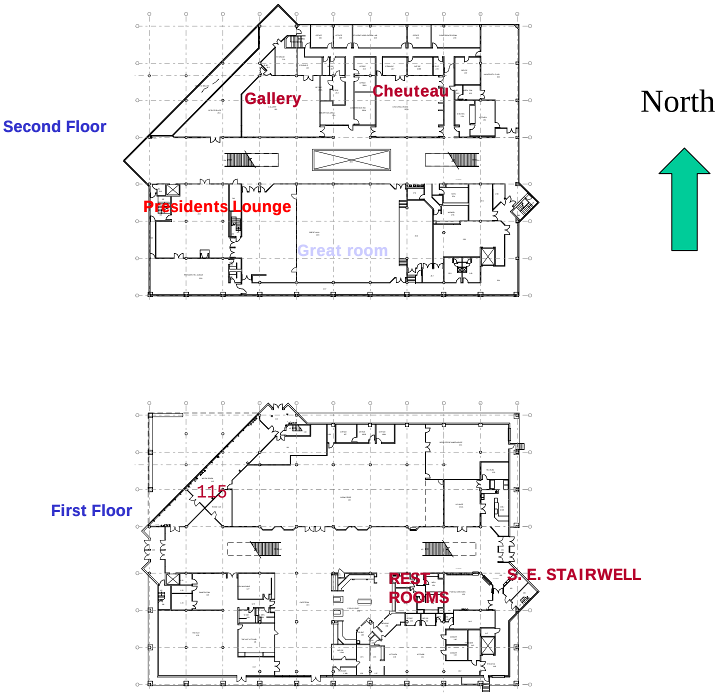
Welcome

Advisory Board Meeting, April 15, 2008

Safety Moment

- Emergency Exits
- Assembly Point – Grassy Area to Northwest
- Tornado Shelter
  - Room 115, Southeast Emergency Stairwell
  - Lower Level Restrooms
- Campus Emergency
  - Call 9-911
  - Campus Security, ext. 5555 or 918-631-5555
- Rest Rooms


The University of Tulsa Campus Map
I-244
E. 3RD STREET
E. 4TH STREET
E. 4TH PLACE
E. 5TH STREET
E. 5TH PLACE
6TH STREET
E. 8TH STREET
E. 10TH STREET
E. 11TH STREET
S. COLUMBIA
S. DELAWARE
S. EVANSTON
S. COLLEGE
S. FLORENCE
S. GARY
S. GARY PLACE
S. HARVARD
N
Assembly Area


Second Floor
Gallery
Cheuteau
Presidents Lounge
Great room
North
First Floor
115
REST ROOMS
S. E. STAIRWELL

Introductory Remarks

- 70th Semi-Annual Advisory Board Meeting
  - TUFFP is 35 Years Old
- Handout
  - Combined Brochure and Slide Copy
- Sign-Up List
  - Please Leave Business Card at Registration Table

Team

- Research Associates
  - Cem Sarica (Director)
  - Holden Zhang (Associate Director)
  - Jim Brill (Director Emeritus)
  - Abdel Salam Al-Sarkhi
  - Mingxiu (Michelle) Li

Team …

- Project Coordinator
  - Linda Jones
- Project Engineer
  - Scott Graham
- Research Technicians/Flow Loop Operators
  - Craig Waldron
  - Brandon Kelsey

Team …

- Computer Manager and Web Master
  - James Miller (On Military Service Leave)

Team …

- TUFFP Research Assistants
  - Kwonil Choi (Ph.D.) – Brazil
  - Gizem Ersoy (Ph.D.) – Turkey
  - Bahadir Gokcal (Ph.D.) – Turkey
  - Kyle Magrini (MS) – USA
  - Anoop Sharma (MS) – India
  - Feng Xiao (MS) – PRC
  - Tingting Yu (MS) - PRC

Guests

- Jeb Bracey, BHP Billiton Petroleum
- Magnus Norsdveen, Scandpower
- Dick Shea, Scandpower

Agenda

- 8:30 Introductory Remarks and Executive Summary
- 9:00 Progress Reports
  - An Experimental and Theoretical Investigation of Slug Flow for High Oil Viscosity in Horizontal and Near-Horizontal Pipes
  - Liquid Entrainment in Annular Two-Phase Flow in Inclined Pipes
- 10:25 Coffee Break

Agenda …

- 10:40 Progress Reports
  - Low Liquid Loading Gas-Oil-Water Flow in Horizontal Pipes – Research Overview
  - Low Liquid Loading Gas-Oil-Water Flow in Inclined Pipes
  - Three Phase Flow Unified Model Update
- 12:00 Lunch

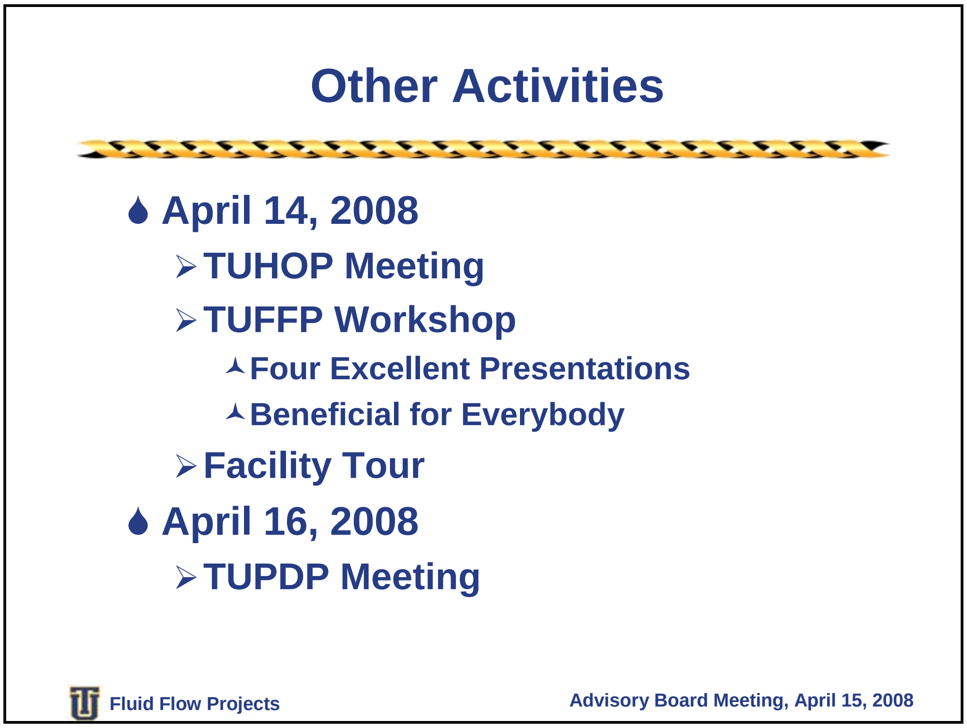
  Allen Chapman Activity Center (ACAC) - Presidents Formal Lounge

Agenda …

- 1:00 Progress Reports
  - New High Viscosity Modeling
  - Investigation of Three-Phase Gas-Oil-Water Flow in Hilly-Terrain Pipelines
  - A Study on Oil-Water Flow Closure Relationships
- 2:15 Coffee Break

Agenda ...

- 2:30 Progress Reports …
  - Up-scaling Studies in Multiphase Flow
  - Lagrangian-Eulerian Transient Two-phase Flow Model
  - Modeling of Gas-Liquid Flow in an Upward Vertical Annulus
- 3:45 TUFFP Business Report
- 4:00 Open Discussion
- 4:30 Adjourn
- 6:00 TUFFP/TUPDP/TUHFP Reception (Reynolds Center – President’s Suite)



Other Activities

- April 14, 2008
  - TUHOP Meeting
  - TUFFP Workshop
    - Four Excellent Presentations
    - Beneficial for Everybody
  - Facility Tour
- April 16, 2008
  - TUPDP Meeting

Fluid Flow Projects

Executive Summary
of Research Activities

Cem Sarica

Advisory Board Meeting, April 15, 2008

High Viscosity Multiphase Flow

- Significance
  - Development of High Viscosity Oil Reserves
- Objective
  - Development of Better Prediction Models
- Past Studies
  - First TUFFP Study by Gokcal
    - Existing Models Perform Poorly for Viscosities Between 200 and 1000 cp.
    - Significantly Different Flow Behavior
      - Dominance of Slug Flow
      - Slug Lengths are Shorter
      - Existence of Significantly Thick Layer of Liquid in Gas Region
      - Significantly Large and Small Size Bubbles Existing in Slug Body

High Viscosity Multiphase Flow …

- Current Study
  - Second TUFFP Study by Gokcal
    - Slug Flow Characteristics such as Translational Velocity, Slug Length are Targeted
  - Status
    - Drift Velocity Experiments are Completed for Viscosities between 200 and 1200 cp at Inclinations Angles from 0° to 85°
    - Horizontal Flow Drift Velocity Model was Developed Based on Benjamin's Approach

High Viscosity Multiphase Flow …

- Near Future Activities
  - Conduct Slug Flow Experiments to Develop Closure Models for Translational Velocity, Slug Holdup and Slug Length
- Future Activities (With New Students)
  - Remaining Closure Relationships
  - Investigate Higher GOR Behavior
  - Investigate Higher Viscosity Oils, μ>1000 cp

Fluid Flow Projects

An Experimental and Theoretical Investigation of Slug Flow for High Oil Viscosity in Horizontal and Near-Horizontal Pipes

Bahadir Gokcal

Advisory Board Meeting, April 15, 2008

Outline

- Significance
- Objectives
- Experimental Facility
- Modeling Study
- Future Work
- Project Schedule

Significance

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

Significance …

- Gokcal (2005, TUFFP) Conducted Experimental Study
- Performance of Existing Models is not Sufficient
- Increasing Oil Viscosity has Significant Effect on Flow Behavior

Objectives

- Acquire Experimental Data on Characteristics of Slug Flow for High Viscosity Oil
- Develop Closure Models on Slug Flow for High Viscosity Oil in Horizontal and Near-Horizontal Pipes
  - Translational Velocity and Drift Velocity
  - Slug Holdup
  - Slug Length/Frequency
- Validate Proposed Models with Experimental Results

Experimental Facility

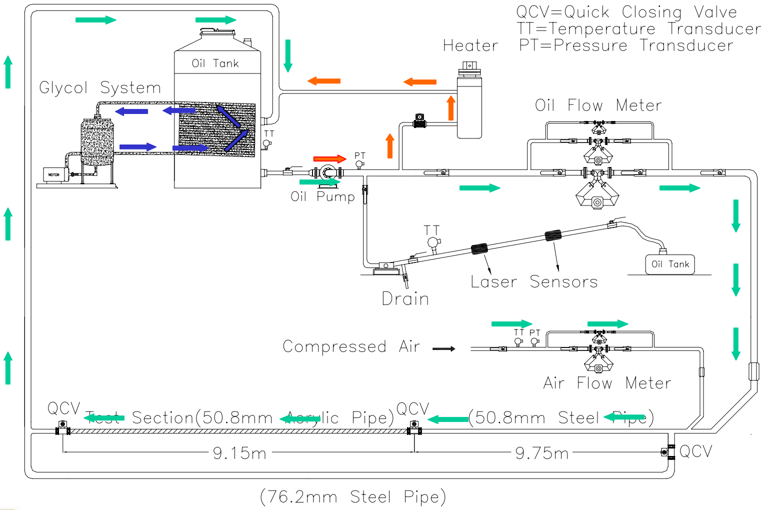
- 2-in ID High Viscosity Indoor Experimental Facility
  - Test Section
  - Metering Section
  - Heating System
  - Cooling System

Experimental Facility …

2-in ID High Viscosity Indoor Facility

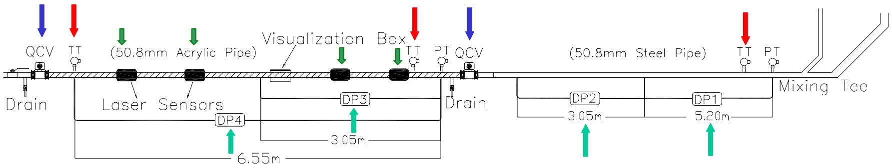
Test Section

Experimental Facility…



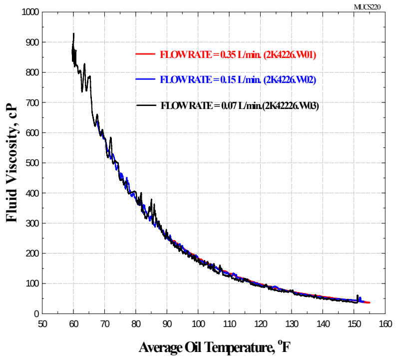
Experimental Facility…

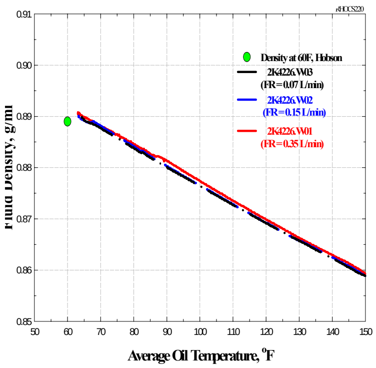
Schematic of Test Section



Test Fluid

Company	Product Name	Grade	°API	Viscosity (40 °C)	Viscosity Index
Citgo	Sentry Oils	220	27.6	220 cp	95

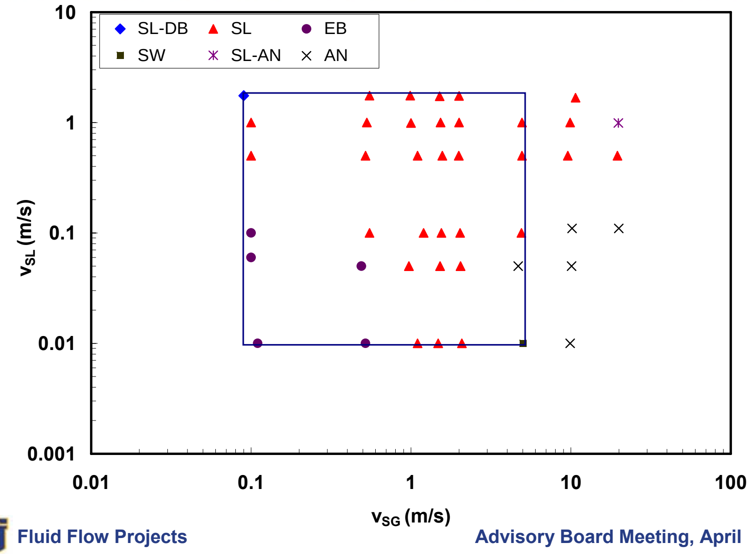




Testing Range

- Focused on Intermittent Flow (Elongated Bubble and Slug Flow)
- Significant Amount of Air Bubbles Entrained in Liquid with Increasing Gas Flow Rate
- New Mixture Appeared as Foam
- Critical Air Velocity Has to Be Known to Prevent Foaming

Testing Range …

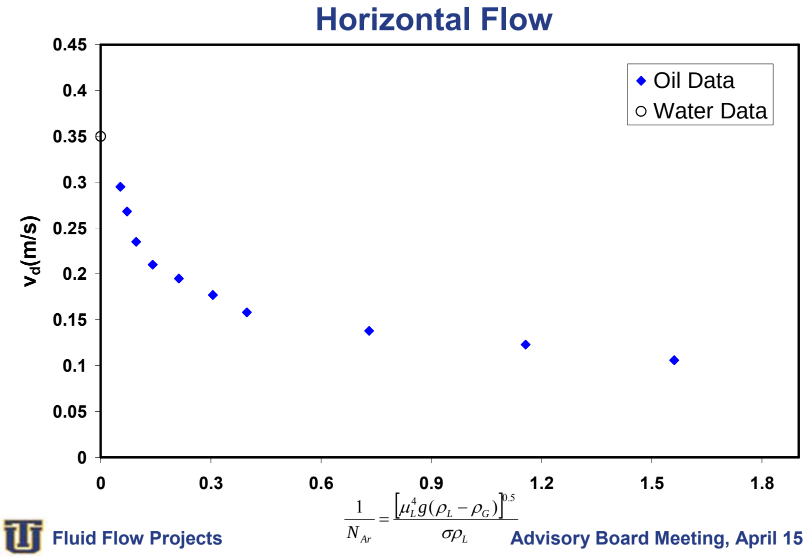


Experimental Results

- Experiments Performed for Horizontal and Inclined Pipes at Different Viscosities
  - Drift Velocity
  - Liquid Height
- Dimensionless Number Preferred in Graph
  - Archimedes Number

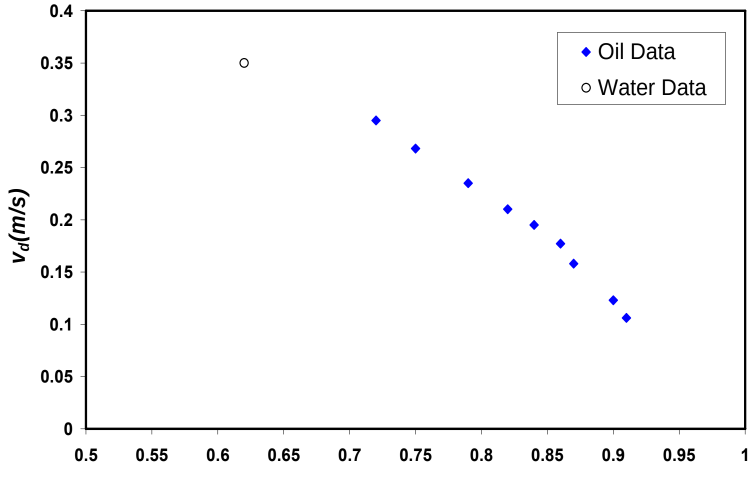
$$N_{Ar} = \frac{\sigma \rho_L}{\left[\mu_L^4 g(\rho_L - \rho_G)\right]^{0.5}}$$

Experimental Results…



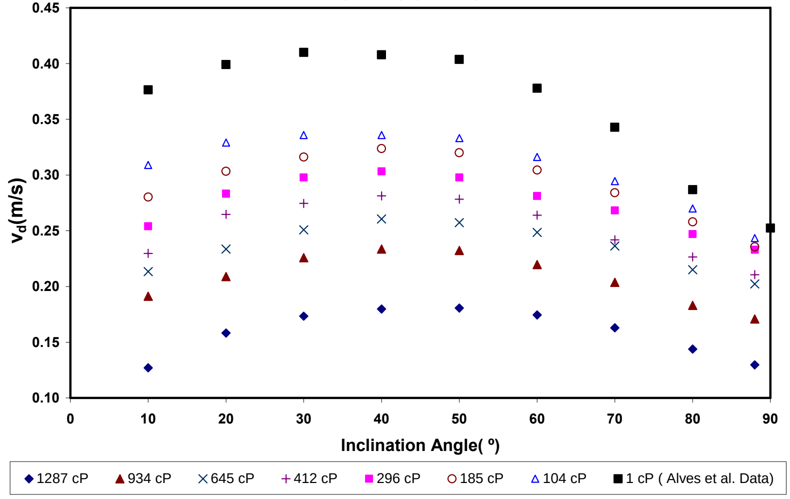
Experimental Results…

Horizontal Flow



Experimental Results…

Inclined Flow



Modeling Study

- Slug Flow Closure Models Need to Be Investigated for High Viscosity Oils
  - Translational Velocity
  - Slug Holdup and Bubble Velocity in Liquid Slug
  - Slug Length/Frequency

Modeling Study…

- Nicklin *et al.* (1962) proposed

$$v_T = C_S v_s + v_D$$

- Dumitrescu (1943) Performed Potential Flow Analysis to Find Drift Velocity for Vertical Flow

$$v_d = 0.351\sqrt{gD}$$

Modeling Study…

- Wallis (1969), Dukler and Hubbard (1975)

"There is No Drift Velocity for Horizontal Case Since Gravity Can Not Act in Horizontal Direction."

- Nicholson *et al.* (1978), Weber (1981), Bendiksen (1984)
  - Drift Velocity Exists For Horizontal Case
- Value of Drift for Horizontal Case Exceeds Vertical Case Value

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Modeling Study…

- Benjamin (1968) Proposed

$$v_d = 0.54\sqrt{gD}$$

- Zukoski (1966) and Bendiksen (1984) Supported Study of Benjamin Experimentally
- Zukoski (1966)
  - Effects of Liquid Viscosity, Surface Tension, Pipe Inclination on Motion of Single Elongated Bubbles in Stagnant Liquid
  - Effect of Viscosity Negligible on Drift Velocity for Re>200

Modeling Study…

- **Bendiksen (1984) Proposed for All Inclination Angles**

$$v_d = v_d^h \cos\theta + v_d^v \sin\theta$$

- **Hasan and Kabir (1986) Proposed for 90º>β>30º**

$$v_d = v_d^v \sqrt{\sin\theta}(1+\cos\theta)^{1.2}$$

Modeling Study…

- **Alves *et al.* (1993)**
  - **Proposed Model for Drift Velocity in Inclined Flow Including Surface Tension**
- **Zukoski (1966), Bendiksen (1984), Hasan and Kabir (1986)**
  - **Maximum Drift Velocity Occur at Intermediate Angle of Inclination Around 40º to 60º from Horizontal**

Modeling Study…

- From Experimental Results, Oil Viscosity Significant Effect on Drift Velocity
- Effect of Surface Tension on Drift Velocity for High Viscosity Oil Investigated
  - Surface Tension Neglected for Inner Diameter Equal or Bigger Than 2-in
- New Mechanistic Model for Drift Velocity Proposed for High Oil Viscosity in Horizontal Pipe

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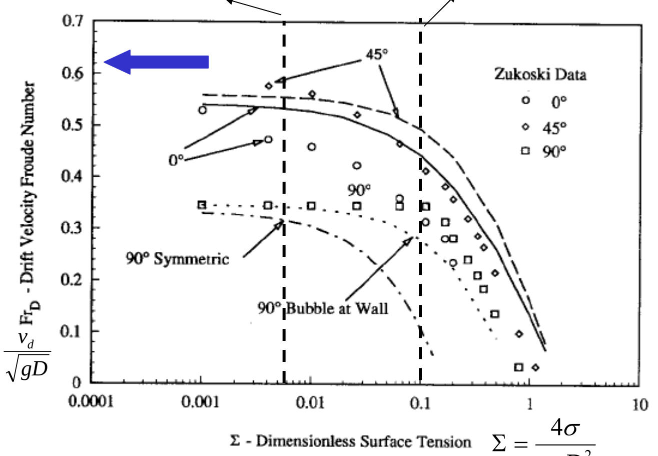
Modeling Study…

2-in ID, σ = 32.5 dynes/cm @ 63 ºF

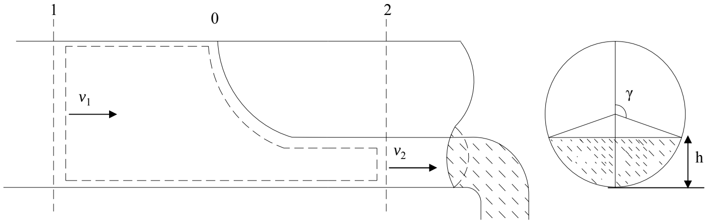
2-in ID, σ = 538 dynes/cm



$$Fr_D = \frac{v_d}{\sqrt{gD}}$$

$$\Sigma = \frac{4\sigma}{\rho g D^2}$$

Preliminary Modeling of Drift Velocity…



- Liquid Draining Out of Horizontal Pipe
- Point “0” Fixed and Point “1” Moving
- Point “0” Taken as Reference Point

Preliminary Modeling of Drift Velocity…

- Continuity Equation Over Control Volume

$$A_1 v_1 = A_2 v_2$$

where A_2 given by $A_2 = \left[\pi - \gamma + \frac{1}{2} Sin2\gamma\right] r^2$

- Continuity Equation can be Expressed

$$\frac{v_1}{v_2} = \frac{A_2}{A_1} = 1 - \zeta \qquad \zeta = \frac{\gamma - \frac{1}{2} Sin2\gamma}{\pi}$$

Preliminary Modeling of Drift Velocity…

- **Bernoulli Theorem Applied Between Point "1" and Stagnation Point "0"**

$$P_1 = -\frac{v_1^2 \rho}{2}$$

- **Bernoulli Theorem Applied Between Point "0" and Point "2" with Inclusion of Viscous Effect**

$$v_2^2 = 2g[r(1-\cos\gamma)-\Delta]$$

Δ= Uniform Loss of Total Head

Preliminary Modeling of Drift Velocity…

- **Momentum Balance Between Points "1" and "2"**

$$(P_1+\rho g r)\pi r^2 - \int_0^h \rho g(h-y)b\,dy - F_f = \rho v_2 A_2 (v_2 - v_1)$$

where F_f given by $F_f = \rho g \Delta A_2$

- **Second Term in Momentum Equation is Pressure Variation with Depth**

$$\int_0^h \rho g(h-y)b\,dy = \rho g r(A_2 Cos\gamma + \frac{2}{3} r^2 Sin^3\gamma)$$

Preliminary Modeling of Drift Velocity…

- Final Form of Momentum Balance

$$\frac{1}{2}(1-\zeta)^2 v_2^2 - (1-\zeta)v_2^2 = gr[(1-\zeta)\cos\gamma + \frac{2}{3\pi}\sin^3\gamma - 1] + \Delta g(1-\zeta)$$

- Expression for v_2^2

$$v_2^2 = \frac{2gr[1-(1-\zeta)\cos\gamma - \frac{2}{3\pi}\sin^3\gamma] - 2\Delta g(1-\zeta)}{1-\zeta^2}$$

Preliminary Modeling of Drift Velocity…

- Total Head Loss Δ

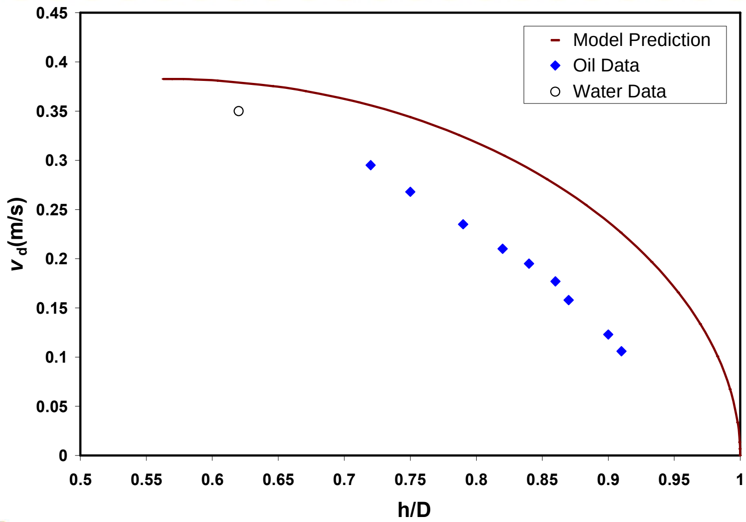
$$\Delta = \frac{(1+\zeta)}{\zeta}\Bigg\{ r(1-\cos\gamma) - \Bigg[\frac{r[1-(1-\zeta)\cos\gamma] + \frac{2}{3\pi}\sin\gamma}{1-\zeta^2}\Bigg]\Bigg]\Bigg\}$$

- Total Head Loss Solved Numerically for Given Angle γ

Preliminary Modeling of Drift Velocity…

- Δ Show Positive Values for γ<82.78º
  - Possible with Energy Loss
- Δ Show Negative Values for γ>82.78º
  - External Supply of Energy Necessary to Maintain Steady Flow
  - Impossible from Practical Point of View
- Δ Equal Zero for γ=82.78º
  - Solution Found By Benjamin for Inviscid Case

Preliminary Modeling of Drift Velocity…



Future Work

- Complete Drift Velocity Study
- Shake Down Tests of Facility
- Conduct Experiments
- Develop Closure Models

Project Schedule

Literature Review	Completed
Facility Modifications	Completed
Preliminary Testing	Underway
Testing	June 2008
Model Development	August 2008
Model Validation	October 2008
Final Report	December 2008

Questions & Comments

Fluid Flow Projects Advisory Board Meeting, April 15, 2008

An Experimental and Theoretical Investigation of Slug Flow for High Oil Viscosity in Horizontal and Near-Horizontal Pipes

Bahadir Gokcal

PROJECTED COMPLETION DATES:

Literature Review	Completed
Facility Modifications	Completed
Preliminary Testing	Underway
Testing	June 2008
Model Development	August 2008
Model Validation	October 2008
Final Report	December 2008

Objectives

The objectives of this study are:

- to acquire experimental data on characteristics of slug flow for high viscosity oil in horizontal and near-horizontal pipes,
- to develop closure models on slug flow for high viscosity oils in horizontal and near-horizontal pipes,
- to validate proposed models with experimental results.

Introduction

High viscosity oils are produced from many oil fields around the world. Oil production systems are currently flowing oils with viscosities as high as 10,000 cp. High viscosity or "heavy oil" has become one of the most important future hydrocarbon resources with the ever increasing world energy demand and the depletion of conventional oils.

Current multiphase flow models are largely based on experimental data with low viscosity liquids. Commonly used laboratory liquids have viscosities less than 20 cp. Thus, the gap between actual laboratory data and field data can be three orders of magnitude or more. Therefore, the current mechanistic models need to be verified with higher liquid viscosity experimental results. Modifications or new developments are necessary.

Almost all flow models have viscosity as an intrinsic variable. Multiphase flows are expected to exhibit significantly different behavior for higher viscosity oils. Many flow behaviors will be affected by the liquid viscosity, including flow pattern, droplet formation, surface waves, bubble entrainment, slug mixing zones, and even three-phase stratified flow.

Gokcal (2005) conducted an experimental study to investigate the effects of high oil viscosity on two-phase oil-gas flow behaviors. The comparison of experimental data against existing models showed that the performances of existing models are not sufficiently accurate for high viscosity oils. It was found that increasing oil viscosity had a significant effect on flow behaviors. Intermittent flow (slug and elongated bubble) was mostly observed in his study. Based on his results, this study is focused the on slug flow region for high viscosity oil. Knowledge of slug flow characteristics is crucial to design pipelines and process equipment. In order to improve the accuracy of slug characteristics for high viscosity oils, accurate closure models for slug flow are needed. The developed expressions will significantly improve the performance of existing two-phase flow models for high viscosity oil applications.

Since the last Advisory Board meeting, the TUFFP High Viscosity Facility (2-in. ID) has been modified, and drift velocity experiments were conducted at different temperatures for horizontal and inclined pipes.

Air-highly viscous oil two-phase flow experiments will continue after the Advisory Board meeting using the 2-in. ID high viscosity indoor facility. Pressure drop and slug characteristics including translational velocity, slug liquid holdup, slug length and frequency will be measured and relevant closure models will be developed.

Experimental Study

Facility

The existing indoor high viscosity test facility will be modified for this experimental study. The facility is comprised of an 18.9-m (62-ft) long, 50.8-mm (2-in.) ID pipe with a 9.15-m (30-ft) long transparent acrylic pipe section to visually observe the flow. The inclination angle can be changed from -2° to 2° from horizontal. A 76.2-mm (3-in.) ID return pipe is connected to the test section with a flexible hose. The return pipe goes to the oil storage tank. A metering section, test section, and heating and cooling systems are the major components of the facility, as shown in Fig. 1.

Compressed air was used as the gas phase, and was supplied by a dry rotary screw air compressor. Oil was pumped by a 20-hp screw pump from an oil storage tank. A motor frequency drive was installed to provide better flow rate control and reduce the amount of heat generated. The oil storage tank contained 3.03 m^3 of oil. Both air and oil flow rates were metered by Micro Motion^{TM} mass flow meters. The fluids were mixed at a mixing tee, flowed through the test section and returned to the oil storage tank. The oil storage tank was also used as a separator. The separated air was discharged outside through a ventilation system.

There are four differential pressure transducers on the facility. Two of them are on the transparent acrylic pipe. The others are on the steel pipe. The purpose of DP1 and DP2 on the steel pipe is to monitor the development of the flow before it reaches the test section. DP3 spans 3.05-m (10-ft) of the transparent pipe is mainly used for high flow rates. DP4 spans 6.55-m (20-ft) of the transparent pipe and is used for low flow rates. Quick-closing valves are used for flow control and liquid trapping. Four laser beams and sensors are used to measure translational velocity, slug frequency, and slug length. The location of each laser beam and sensor can be changed easily along the pipe. In addition, two Resistance Temperature Detector (RTD) temperature transducers located at the inlet and outlet of the test section are used to measure temperatures. The temperature measurements are imperative to determine the viscosity of the oil during experiments. A TUFFP high speed video system is used to identify the flow patterns. A visualization box is installed on the acrylic pipe to observe and record flow patterns in details. A schematic of the test section is shown in Fig. 2.

For drift velocity experiments, some additional modifications were made to the existing facility without changing the original structure. The objective of this modification is to determine the effect of high oil viscosity on the drift velocity for horizontal and upward inclined pipes. In order to measure drift velocity in horizontal pipe, one of the quick-closing valve located at the end of the test section was modified, and can be opened to the atmosphere manually. Therefore, the trapped oil can be drained from the horizontal pipe. The drift velocity is measured by two laser beams and sensors. For drift velocity experiments at different inclination angles, a 3.05-m (10-ft) long transparent acrylic pipe with 50.8-mm (2-in.) ID was added to the existing facility temporarily, as shown in Fig. 1. The acrylic pipe is located close to the oil storage tank. The inclination angle can be changed from 0° to 90°. The oil pump is used to fill up the pipe at various temperatures corresponding to different viscosities. The oil can be captured by valves which are located at the inlet and outlet of the pipe. An air bubble from the bottom of the pipe is released into the stagnant liquid column. The drift velocity of the released air bubble is measured by two laser beams and sensors.

Test Fluid

The Citgo Sentry 220 oil used in the previous study is used again as the test fluid. Following are typical properties of Citgo Sentry 220 oil:

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

The viscosity and oil density vs. temperature behavior for Citgo Sentry 220 oil are shown in Figs. 3 and 4, respectively.

Experimental Range

Elongated bubble and slug flows were mostly observed during high viscosity experiments. This study is focused on intermittent flow (elongated bubble and slug flow) for high viscosity oils.

It is known that a significant amount of air bubbles can be entrained in liquid with increasing gas flow rate. The diameter of air bubbles gets smaller with increasing gas flow rates and the color of the oil changes completely. The new mixture can exist as foam, and foam is a major challenge for separation. Therefore, a critical air velocity has to be known to prevent foam formation in the experimental study. Experimental observations were used to determine the critical gas velocity that gives transition from air bubbles to foam. All video recordings were investigated carefully. It was found that the critical gas velocity was 5 m/s. If the gas velocity is higher than this velocity, foaming will be observed.

Figure 5 shows the experimental observations of flow patterns for an oil viscosity of 0.181 Pa·s. The marked area in the flow pattern shows the velocity limits for future high oil viscosity experiments. The superficial liquid and gas velocities can range from 0.01 to 1.75 m/s and from 0 to 5 m/s, respectively.

Preliminary Experimental Results

After the facility was commissioned, drift velocity experiments were performed. The experiments were conducted at different oil viscosities and inclination angles. Currently, the facility is being prepared to conduct slug flow experiments for high viscosity oils in horizontal and near-horizontal pipes.

Drift Velocity:

Initially, an experiment was conducted with water to prove that the system was working properly. The results for water were compared with Benjamin's model (1968) prediction. The predictions of drift velocity and liquid height of the water from Benjamin's model show excellent agreement with the data. The calculated drift velocity and liquid height parameter (h/D) were 0.38 m/s and 0.563, respectively, while the measured drift velocity and liquid height for water were 0.35 m/s and 0.62.

The rest of the experiments were performed at temperatures between 66.5 ºF (19.2 ºC) and 113 ºF (45 ºC) using the Citgo Sentry 220 oil and horizontal pipe. The oil viscosities corresponding to the test temperatures were 121 cP (0.121 Pa·s) and 692 cP (0.692 Pa·s), respectively. The drift velocity and liquid height of the oil were measured at different oil viscosities.

The dimensionless Archimedes number, N_{Ar} is applied in Fig. 6 to show viscosity, surface tension, fluid properties and gravitational acceleration parameters in one equation. Wallis (1969) proposed N_{Ar}, as

$$N_{Ar} = \frac{\sigma \rho_L}{\left[\mu_L^4 g(\rho_L - \rho_G)\right]^{0.5}} \tag{1}$$

Figure 6 shows the experimental results for drift velocity vs. Archimedes number. It is seen that the effect of high viscosity plays an important role on the drift velocity. The drift velocity decreases with a decrease in Archimedes number and with an increase of oil viscosity.

Drift velocity versus liquid height from the conducted experiments are plotted in Fig. 7. The drift velocity decreases with an increase of liquid height and oil viscosity. The lowest liquid height and the highest drift velocity are found for water. They also match the results obtained from the Benjamin model using inviscid flow theory.

Experiments were performed at temperatures between 51 ºF (10.6 ºC) and 122 ºF (50 ºC) using Citgo Sentry 220 oil for inclination angles of 10º to 88º. The oil viscosities corresponding to the above temperatures are 107 cP (0.107 Pa·s) and 1287 cP (1.287 Pa·s), respectively.

The change of drift velocity with inclination angle and viscosity is given in Fig. 8. Alves *et al.* (1993) data for water are shown in the same graph to understand the effect of high liquid viscosity. The results show that the dependence of drift velocity on viscosity is significant. The drift velocity decreases with the increase of oil viscosity. It increases with an increase in inclination angle, reaching a maximum at about 40° from horizontal, and then decreases to a lowest value for vertical pipe.

Modeling Study

Slug flow closure models need to be investigated for high viscosity oil and gas two-phase flow. The closure models include translational velocity, slug holdup and bubble velocity in the liquid slug region, slug length and frequency.

Preliminary Modeling of Drift Velocity

The slug translational velocity or velocity of slug units is one of the key closure relationships in two-phase flow mechanistic modeling. Translational velocity is described as a superposition of bubble velocity in stagnant liquid, i.e. the drift velocity v_d and the maximum axial velocity in the slug body. Nicklin et al. (1962) proposed an equation for translational velocity as,

$$v_t = C_s v_s + v_d \, . \tag{2}$$

The parameter C_s is approximately the ratio of the maximum to the mean velocity of a fully developed velocity profile. C_s equals approximately 1.2 for turbulent flow and 2.0 for laminar flow.

Dumitrescu (1943) performed a potential flow analysis to find the drift velocity for vertical flow and proposed the following equation:

$$v_d = 0.351\sqrt{gD} \, . \tag{3}$$

Equation 3 was confirmed by the air/water experimental data of Nicklin *et al.*

Zukoski (1966) experimentally investigated the effects of liquid viscosity, surface tension, pipe inclination on the motion of single elongated bubbles in stagnant liquid for different pipe diameters. He also found that the effect of viscosity is negligible on the drift velocity for $Re = v_d \rho D / \mu > 200$.

Wallis (1969) and Dukler and Hubbard (1975) claimed that there is no drift velocity for horizontal flow since gravity can not act in the horizontal direction. However, Nicholson *et al.* (1978), Weber (1981), and Bendiksen (1984) showed that drift velocity exists for the horizontal case and the value of drift velocity can exceed the vertical flow value. The drift velocity is a result of hydrostatic pressure difference between the top and bottom of the bubble nose.

For the drift velocity, Benjamin proposed the following relationship for horizontal pipes,

$$v_d = 0.542\sqrt{gD} \, . \tag{4}$$

Benjamin calculated the value of the drift velocity coefficient by using inviscid (potential) flow theory (surface tension and viscosity are neglected). The drift velocity in horizontal slug flow is the same as the velocity of the penetration of a bubble when liquid is drained out of a horizontal pipe. Bendiksen and Zukoski supported the study of Benjamin (1968), experimentally.

For the inclined case, Zukoski, Bendiksen, Weber *et al.*, Hasan and Kabir (1986), and Carew *et al.* (1995) experimentally studied drift velocity and found that a maximum drift velocity occurs at an intermediate angle of inclination around 40º to 60º from the horizontal.

Bendiksen performed an experimental study for velocities of single elongated bubbles in flowing liquids at different inclination angles. He proposed the following equation for all inclination angles:

$$v_d = v_d^h \cos\theta + v_d^v \sin\theta \, . \tag{5}$$

where, v_d^h and v_d^v are drift velocities for horizontal and vertical flow, respectively.

Hasan and Kabir performed an experimental study in the range of $90^\circ > \Theta > 30^\circ$ and proposed the relation:

$$v_d = v_d^v \sqrt{\sin\theta}\,(1+\cos\theta)^{1.2} \, . \tag{6}$$

Alves et al. (1993) proposed a model for the drift velocity in inclined flow using inviscid flow theory and taking surface tension effects into consideration. The model was compared against their experimental data and Zukoski's data. The model showed good agreement with the experimental results.

Carew *et al.* studied the motion of long bubbles in inclined pipes experimentally with viscous Newtonian and non-Newtonian liquids. He proposed an empirical correlation for the drift velocity of elongated bubble in inclined pipes.

The literature review shows that there is no available study or model taking into account viscosity effects on drift velocity. Drift velocity is expected to be affected significantly with increasing oil viscosity.

As observed from experimental results, oil viscosity has a significant effect on drift velocity and must be considered. Also, the effect of surface tension on drift velocity must be investigated. Figure 9 shows a comparison of Zukoski's data against the predictions with the Alves' model. The drift velocity, in terms of a Froude number ($Fr = v_d/(gD)^{0.5}$), is plotted against the dimensionless surface tension ($\Sigma = 4\sigma/\rho g D^2$).

There are four curves on the graph. The first (solid line) one is the model prediction of the effect of surface tension for the horizontal case. The second curve is developed for 45º. For the vertical case, two curves are shown; one curve is generated using the inclined model and the other one is developed using the symmetric bubble model. The models gave good agreement with experimental results. For high viscosity oil, the value of Σ is calculated for 2-in ID pipe and found to be 0.006. The result is marked in Fig. 9. For a dimensionless surface tension at 0.1, the resultant surface tension is 538 dynes/cm for 2-in ID. This value is higher than the surface tension of mercury and is unreasonable on intuitive grounds. Figure 9 shows that the effect of surface tension on drift velocity is negligible for high viscosity oil when the inner diameter ≥2-in. Therefore, a new mechanistic model for drift velocity in horizontal pipe is developed considering the effect of high oil viscosity. The proposed drift velocity model can easily be implemented into translational velocity closure relationship to improve the performance of existing two-phase flow models for high viscosity oil.

By extending the Benjamin analysis for the horizontal case, a new model is developed for high viscosity oil to predict the drift velocity in horizontal pipe. Consider a gas pocket draining out of a horizontal pipe, as shown in Fig. 10. It is assumed that point "0" is a stagnation point and point "1" is moving. Moreover, point "0" is taken as a reference point. The value of pressure is zero along the free surface from points "0" to "2".

A continuity equation can be written over the control volume shown in Fig. 10,

$$A_1 v_1 = A_2 v_2 \,. \tag{7}$$

where A_2 is the cross sectional area covered by liquid and is given by

$$A_2 = \left[\pi - \gamma + \frac{1}{2}\sin 2\gamma \right] r^2 \,. \tag{8}$$

The continuity equation can also be expressed as follows:

$$\frac{v_1}{v_2} = \frac{A_2}{A_1} = 1 - \zeta \,. \tag{9}$$

$$\zeta = \frac{\gamma - \frac{1}{2}\sin 2\gamma}{\pi} \,. \tag{10}$$

The Bernoulli theorem is applied between point "1" and stagnation point "0" along the upper boundary. The pressure at point "1" yields

$$P_1 = -\frac{v_1^2 \rho}{2} \,. \tag{11}$$

The Bernoulli theorem is also applied between points "0" and "2" with the inclusion of the viscous effect similar to the procedure of Benjamin in his solution of the two dimensional flow between two infinite parallel plates. It is assumed that the flow undergoes a uniform loss of its total head Δ. The pressure at the stagnation point is the same as the pressure in the gas bubble. The velocity at point "2" is obtained as follows:

$$v_2^2 = 2g[r(1 - \cos\gamma) - \Delta] \,. \tag{12}$$

A momentum balance between points "1" and "2" is given by

$$(P_1 + \rho g r)\pi r^2 - \int_0^h \rho g(h - y) b\,dy - F_f = \rho v_2 A_2 (v_2 - v_1) \tag{13}$$

where the friction force F_f is given by,

$$F_f = \rho g \Delta A_2 \,. \tag{14}$$

The second term in Eq. (13) is the pressure variation with depth, which is hydrostatic. The integral term is solved explicitly,

$$\int_0^h \rho g(h - y) b\,dy = \rho g r\left(A_2 \cos\gamma + \frac{2}{3} r^2 \sin^3\gamma\right) \tag{15}$$

The final form of the momentum balance can be written as

$$\frac{1}{2}(1 - \zeta)^2 v_2^2 - (1 - \zeta) v_2^2 = gr\left[(1 - \zeta)\cos\gamma + \frac{2}{3\pi}\sin^3\gamma - 1\right] + \Delta g(1 - \zeta) \,. \tag{16}$$

An expression for v_2^2 is then obtained as follows:

$$v_2^2 = \frac{2gr\left[1 - (1 - \zeta)\cos\gamma - \frac{2}{3\pi}\sin^3\gamma\right] - 2\Delta g(1 - \zeta)}{1 - \zeta^2} \tag{17}$$

Equating Eqs. (12) and (17) for v_2^2, the total head loss Δ can be written as:

$$\Delta = \frac{(1+\zeta)}{\zeta}\left\{ r(1-\cos\gamma) - \left[\frac{r[1-(1-\zeta)\cos\gamma] + \frac{2}{3\pi}\sin\gamma}{1-\zeta^2} \right] \right\} \tag{18}$$

For a given angle γ, the total head loss Δ can be calculated. The numerical results of the total head loss Δ show positive values for angles less than 82.78º, which corresponds to a liquid height of 0.563 in. for 2-in. ID pipe. This appears to be possible with energy loss. For angles greater than 82.78º, the numerical values of the head loss are negative, which implies that an external supply of energy would be necessary to maintain a steady flow. Therefore, the case for an angle smaller than 82.78º is impossible from a practical point of view. The solution for an angle equal to 82.78º (where the sign of the total head loss is changed) is the same as the solution that found by Benjamin for the inviscid case.

In model predictions, the drift velocity decreases considerably with an increase in liquid height (h/D) and eventually reaches zero when the liquid height is one. The comparison of model predictions with measured drift velocities for horizontal pipe shows fair agreement seen in Fig. 11. The difference between the measured and predicted drift velocity decreases with decreasing liquid height. This may be partly due to the improvement of the measurement uncertainty as liquid height decreases.

Future Studies

The main tasks for the future are:

- Complete the modeling study of drift velocity for inclined pipes.
- Shake down tests of the facility.
- Conduct experiments.
- Develop closure models.

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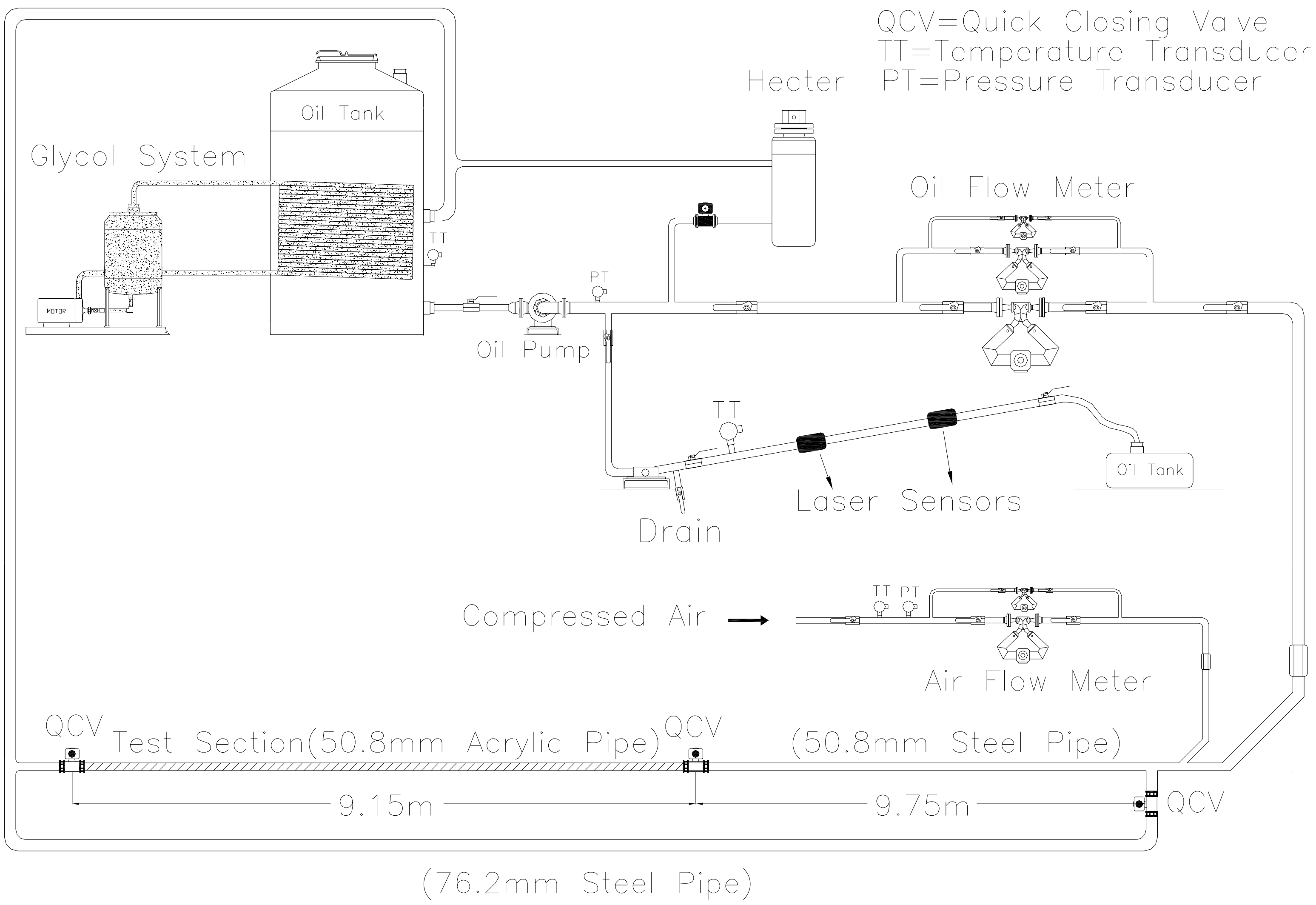

Figure 1 - Schematic of Test Facility

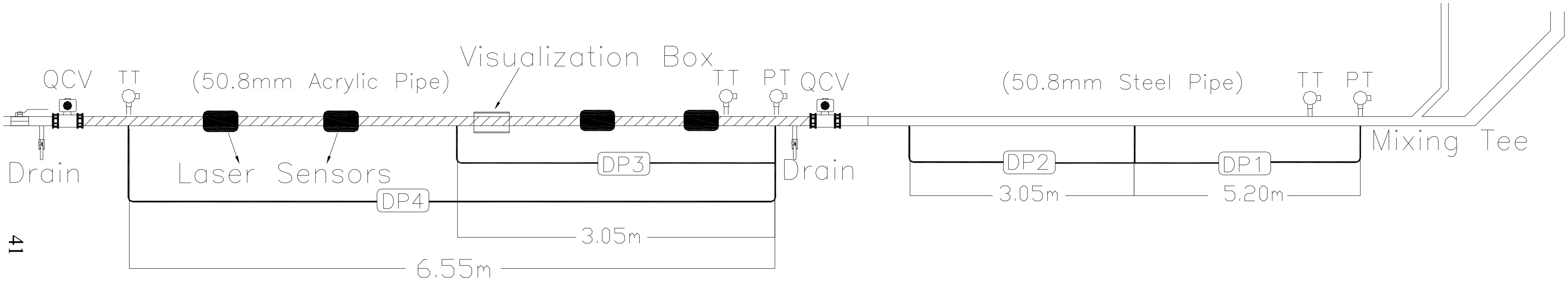

Figure 2 - Schematic of Test Section

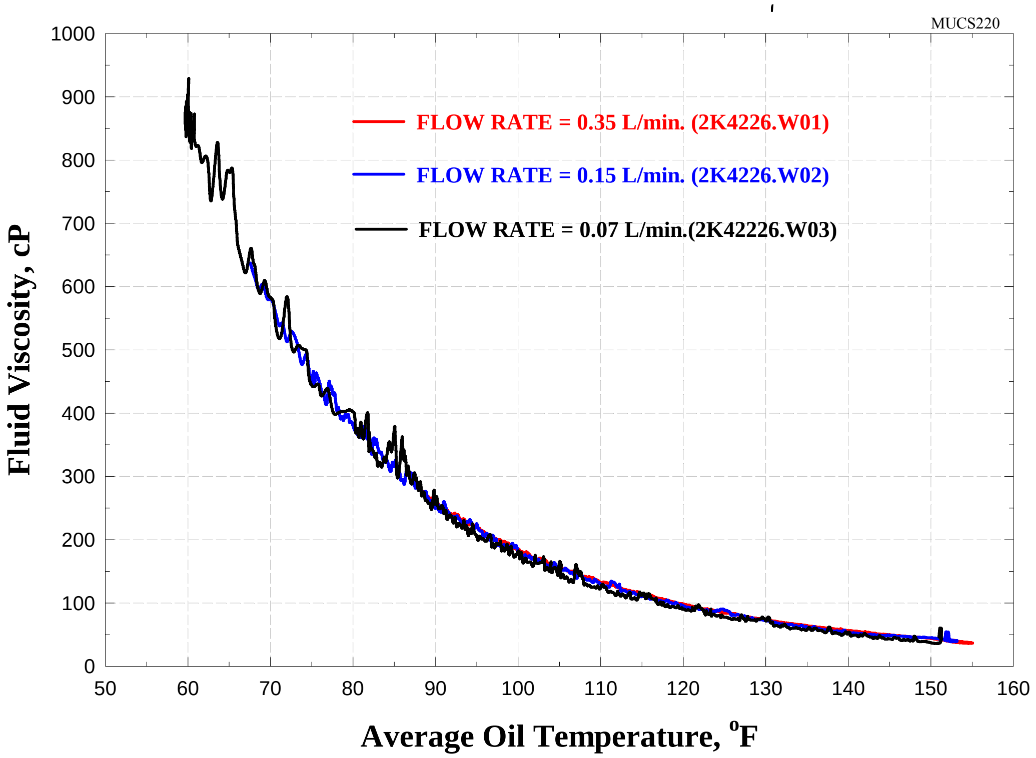

Figure 3 - Viscosity vs. Temperature for Citgo Sentry 220 Oil

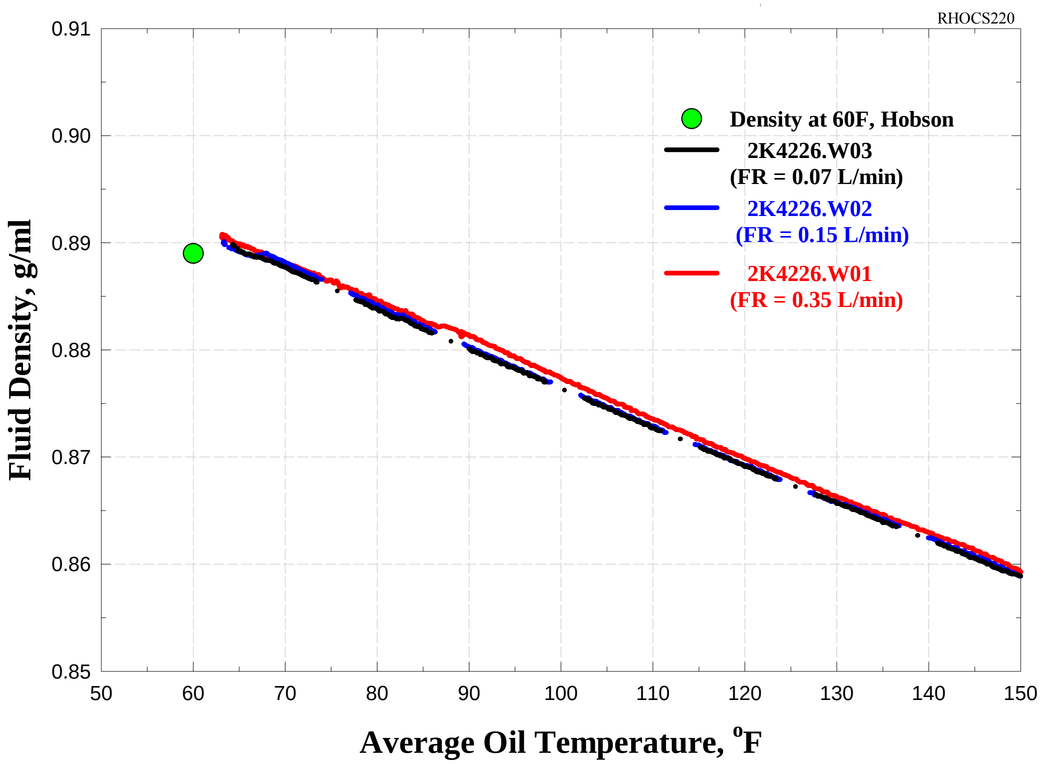

Figure 4 - Oil Density vs. Temperature for Citgo Sentry 220 Oil

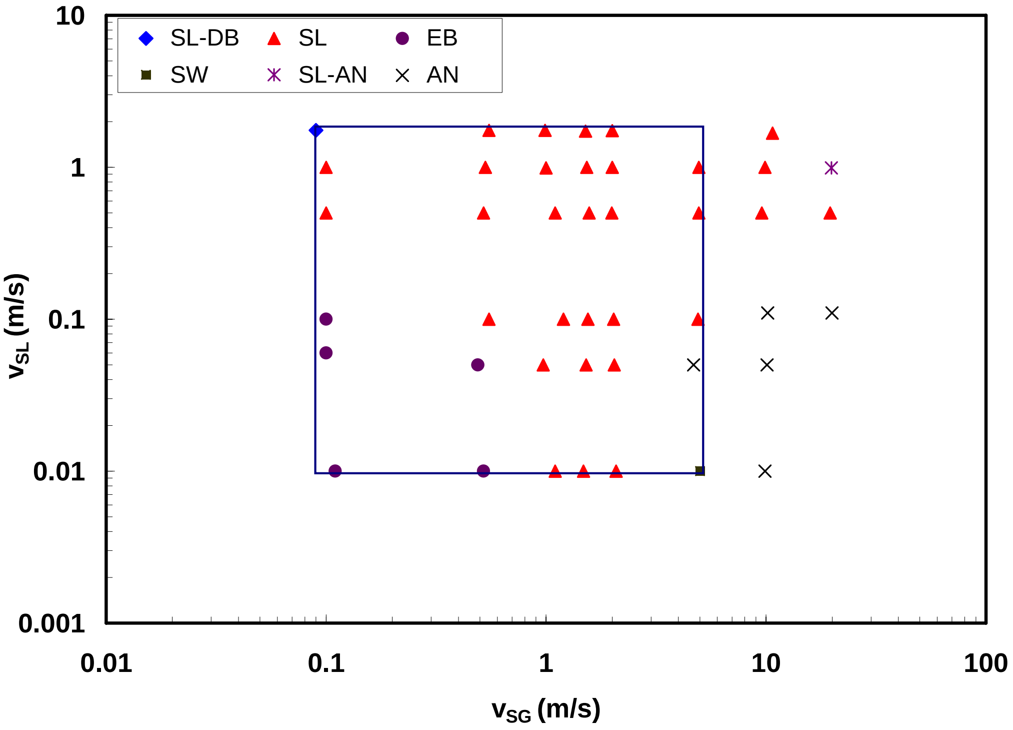

Figure 5 - Experimental Observation of Flow Patterns (0.181 Pa·s or 181 cP)

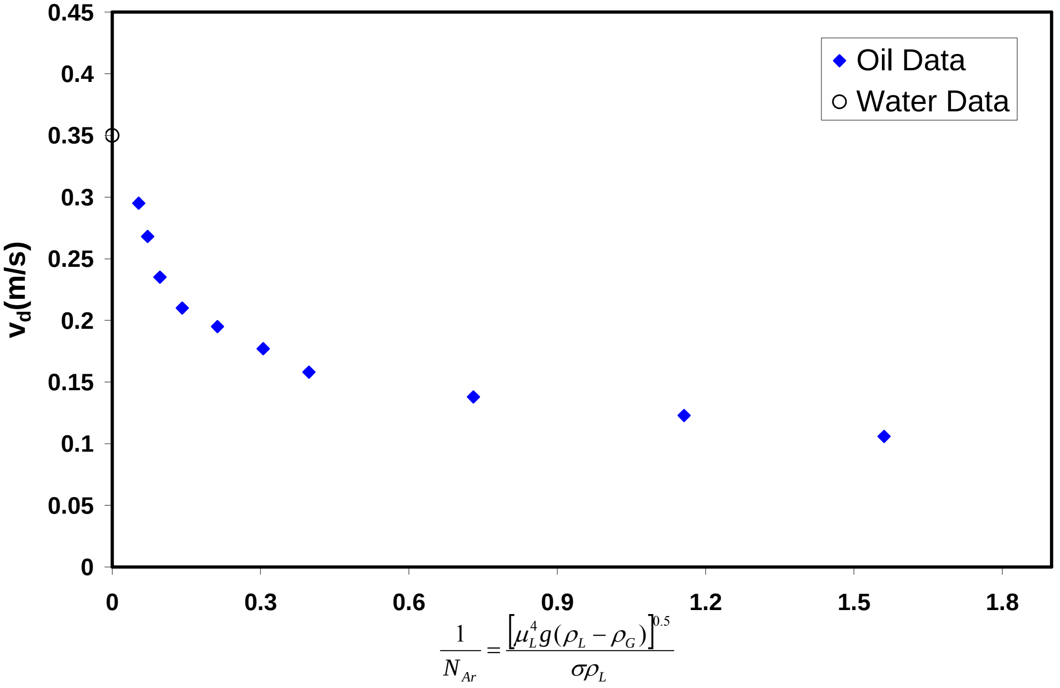

Figure 6 – Measured Drift Velocities vs. Inverse Archimedes Number

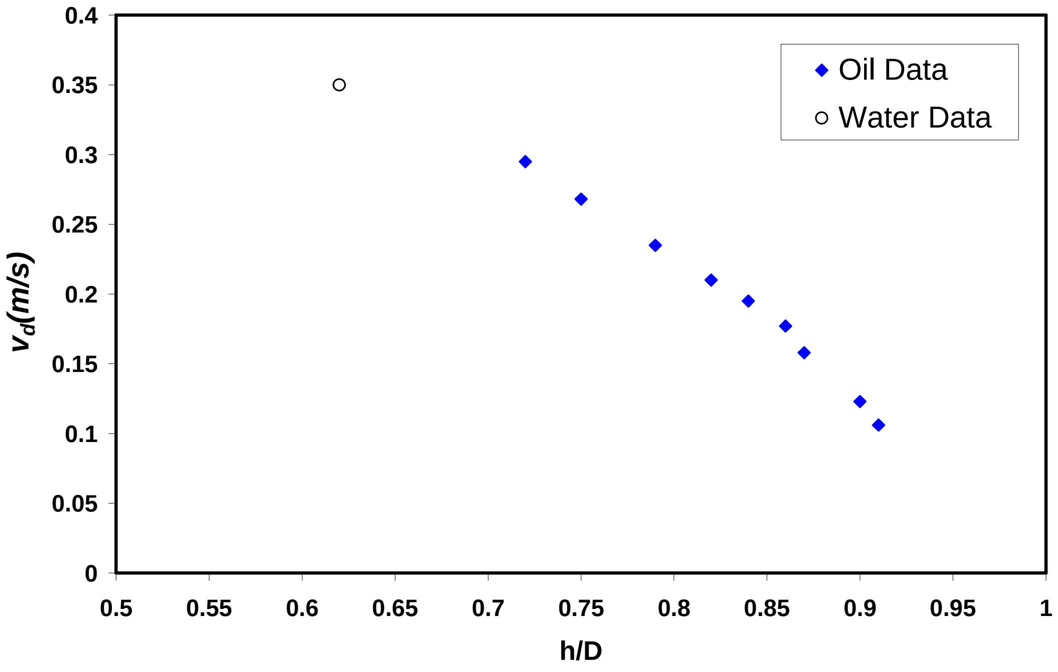

Figure 7 – Measured Drift Velocities vs. Liquid Height

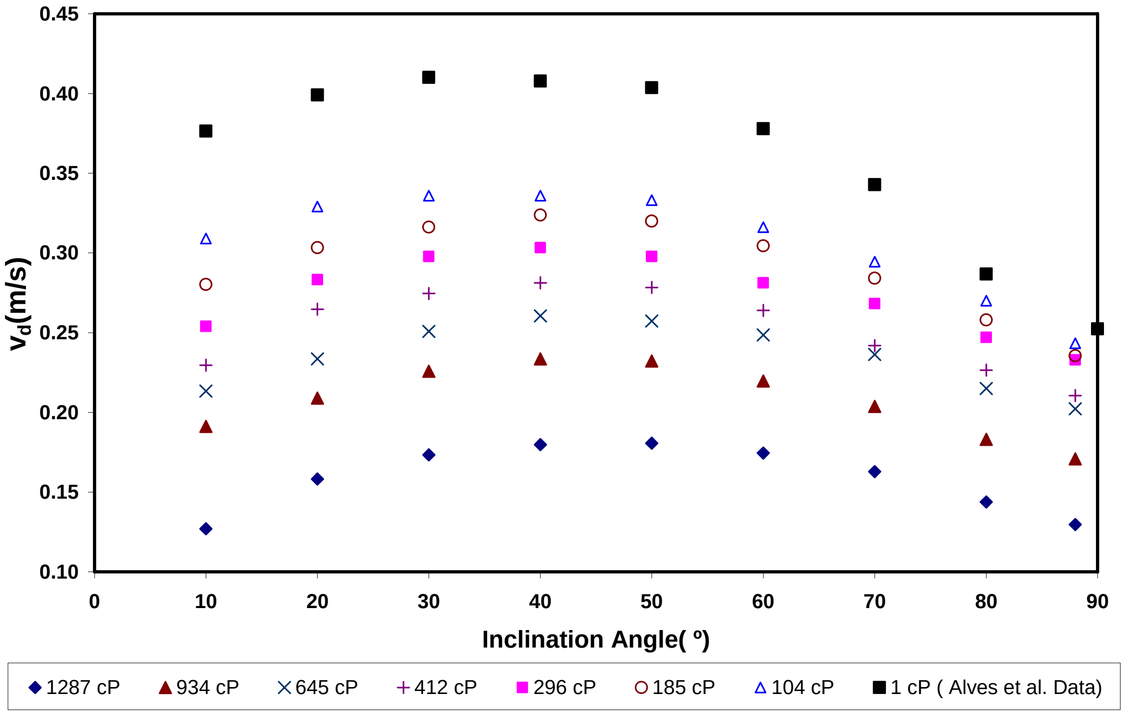

Figure 8 – Measured Drift Velocities vs. Inclination Angle

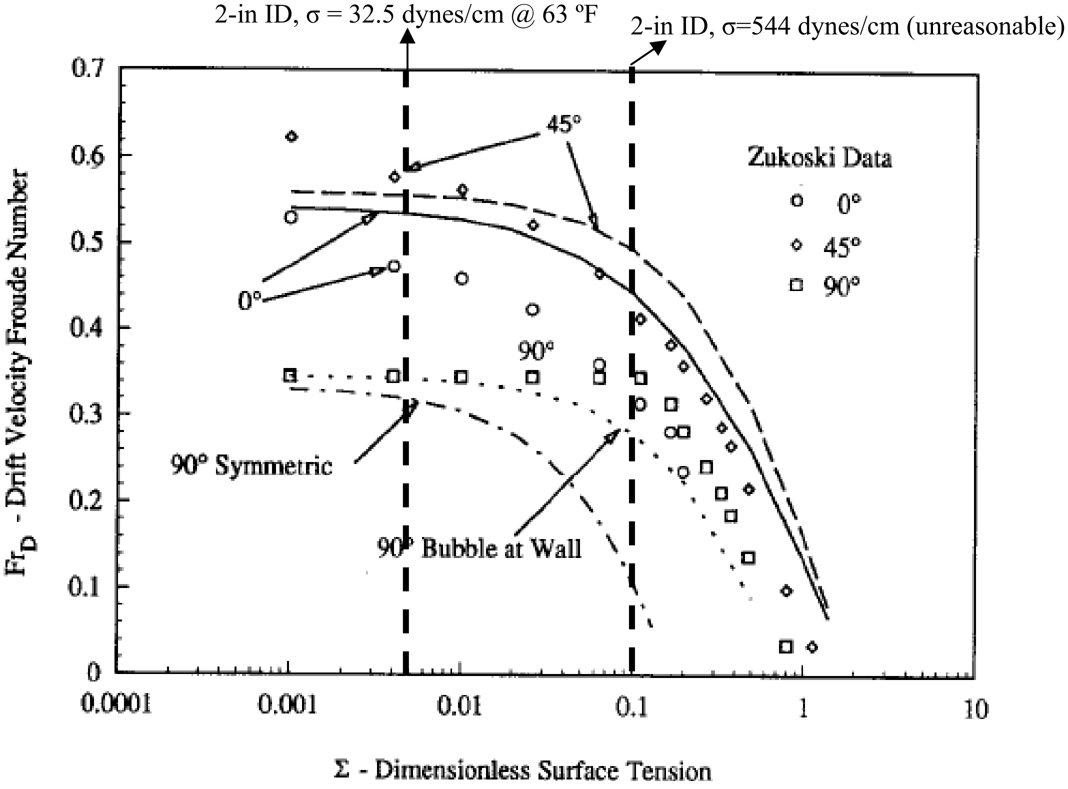

Figure 9 – Effect of Surface Tension on Drift Velocity (Alves, 1993)

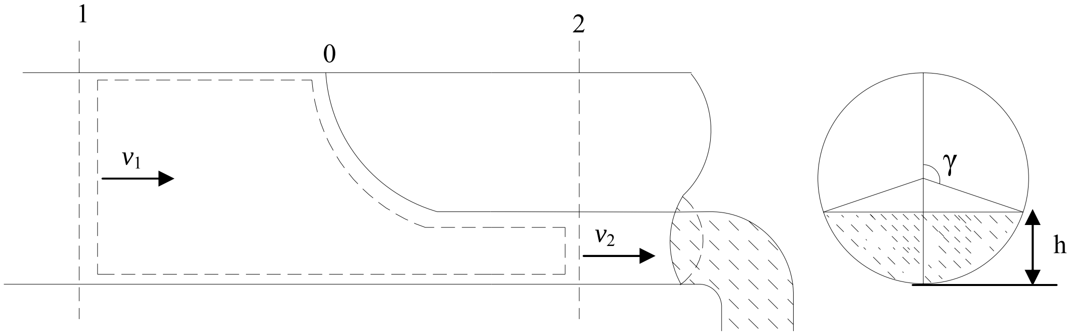

Figure 10 - Propagation of Gas Pocket in Draining Horizontal Pipe

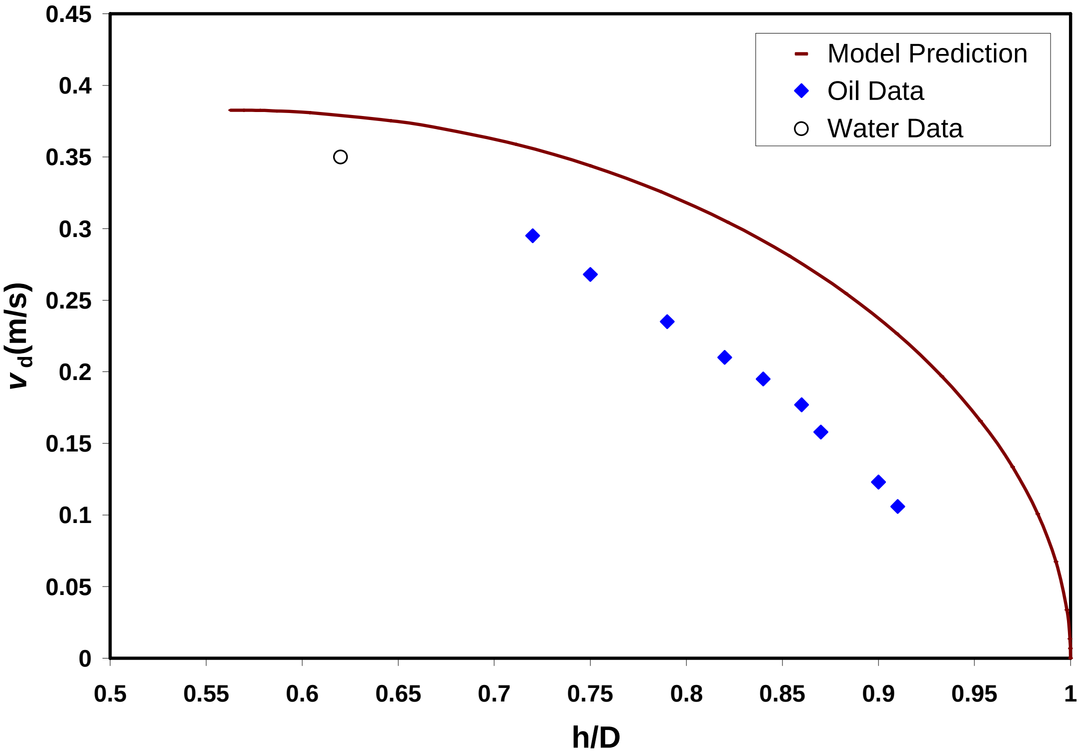

Figure 11 - Comparison of Model Predictions with Measured Drift Velocities

Droplet Homo-phase Studies

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

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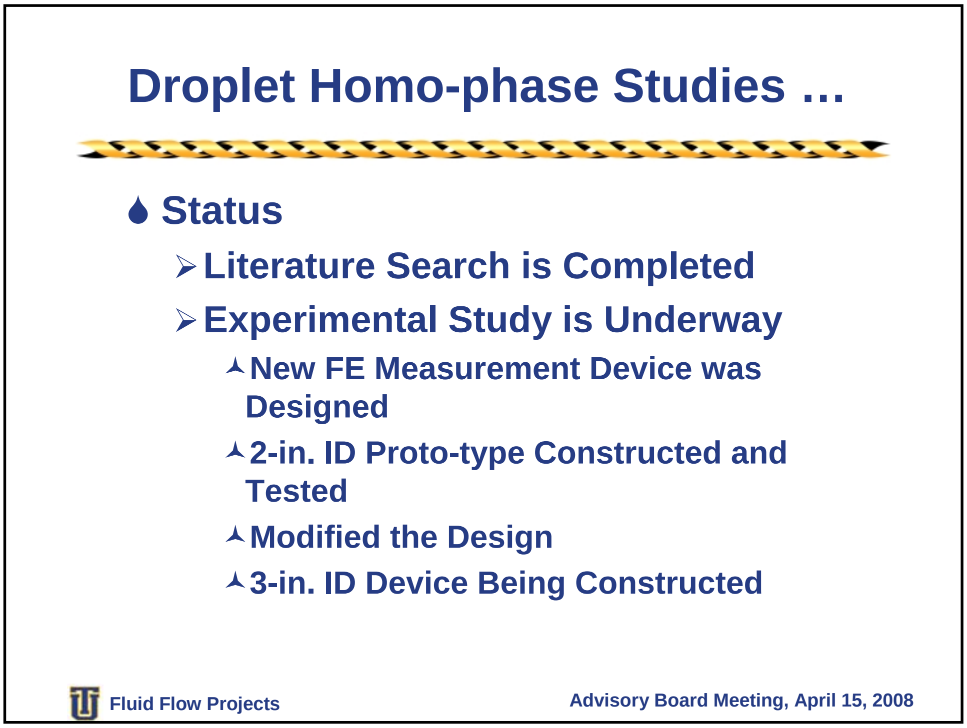
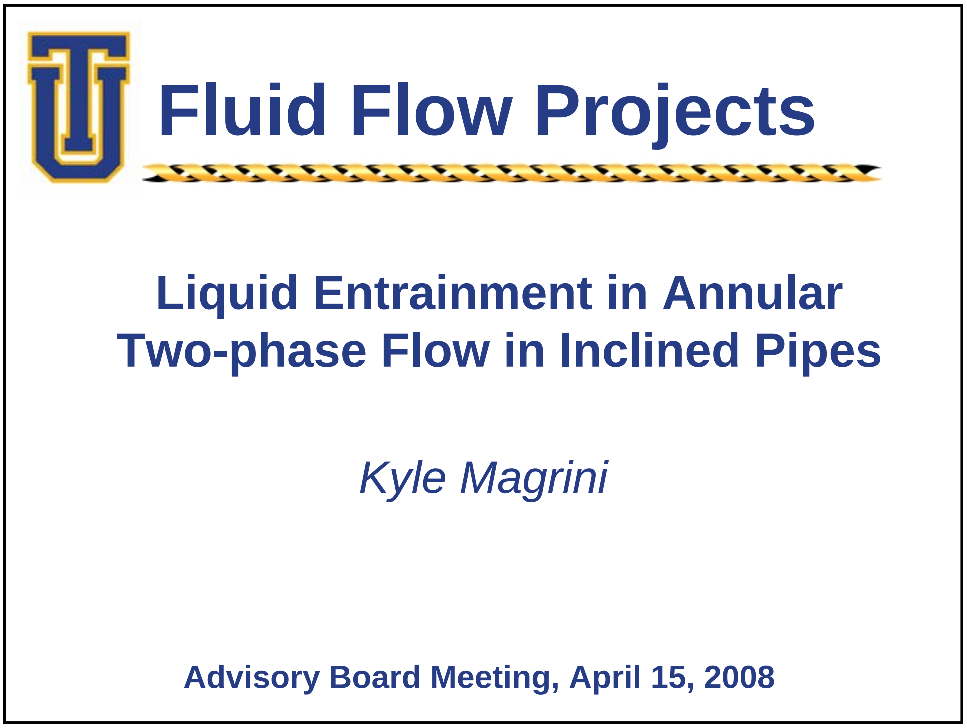
Droplet Homo-phase Studies …

- Current Study
  - Magrini is Studying Liquid Entrainment in Annular Two-Phase Flow in Inclined Pipes
  - Objectives
    - Acquire Data for Various Inclination Angles for 3-in. ID Pipe Using Severe Slugging Facility
      - Existing Data are for 1 and 1 ½ in.
    - Develop a New Closure Relationship



Droplet Homo-phase Studies …

- Status
  - Literature Search is Completed
  - Experimental Study is Underway
    - New FE Measurement Device was Designed
    - 2-in. ID Proto-type Constructed and Tested
    - Modified the Design
    - 3-in. ID Device Being Constructed

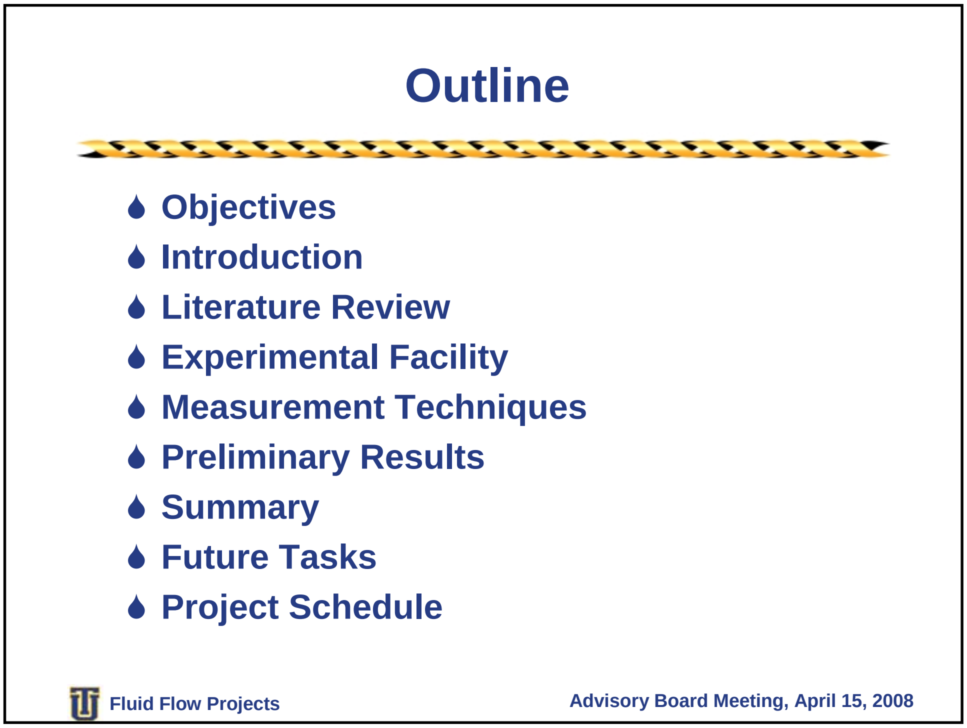


Fluid Flow Projects

Liquid Entrainment in Annular Two-phase Flow in Inclined Pipes

Kyle Magrini

Advisory Board Meeting, April 15, 2008



Outline

- Objectives
- Introduction
- Literature Review
- Experimental Facility
- Measurement Techniques
- Preliminary Results
- Summary
- Future Tasks
- Project Schedule

Objectives

- Acquire Experimental Data of Entrainment Fraction in Two-Phase Gas-Liquid Annular Flow for Inclination Angles from Horizontal of 0^{o}, 10^{o}, 20^{o}, 45^{o}, 75^{o}, and 90^{o}
- Compare Data with Current Correlation and Model Predictions
- Improve Existing Models with New Correlation

Introduction

- Multiphase Flow Mechanistic Models are Tools in Multiphase Design and Applications
  - Pressure Gradient
  - Liquid Holdup
  - Temperature Gradient
  - Etc.

Introduction…

- These Mechanistic Models (e.g. TUFFP Unified Model) Require Closure Relationships
  - Interfacial Friction Factor
  - Droplet Entrainment Fraction
  - Slug Translational Velocity
  - Etc.

Introduction…

- Chen (2005a) Sensitivity Study Showed that for Annular Flow the TUFFP Unified Model and Xiao Model are Most Sensitive to Droplet Entrainment Fraction Compared to Other Closure Relationships

Literature Review

- Vertical Flow Entrainment Fraction Correlations
- Horizontal Flow Entrainment Fraction Correlations
- Inclined Flow Entrainment Fraction Correlations

Vertical Flow

- Wallis (1968)

$$F_E = 1 - \exp\left[-0.125 \times \left(10^4 \frac{v_{SG}\mu_G}{\sigma}\sqrt{\frac{\rho_G}{\rho_L}} - 1.5\right)\right]$$

- Dallman (1978)

$$R_E = R_D$$

$$\frac{F_E}{F_{E,\max}} = \frac{\frac{k_E}{4k_D} d\sqrt{\rho_G \rho_L} v_{SG}{}^3}{1 + \frac{k_E}{4k_D} d\sqrt{\rho_G \rho_L} v_{SG}{}^3} \quad \text{where } \mathrm{F}_{E,\max} = 1 - \frac{W_{LC}}{W_L}$$

Vertical Flow …

- **Oliemans et al. (1986)**

$$\frac{F_E}{1-F_E} = 10^{-2.52} \rho_L{}^{1.08} \rho_G{}^{0.18} \mu_L{}^{0.27} \mu_G{}^{0.28} \sigma^{-1.8} d^{1.72} v_{SL}{}^{0.7} v_{SG}{}^{1.44} g^{0.46}$$

- **Ishii and Mishima (1989)**

$$F_E = \tanh\left[7.25\times10^{-7} We_{SG}{}^{1.25} \left(\frac{\rho_L-\rho_G}{\rho_L}\right)^{\frac{1.25}{3}} \mathrm{Re}_{SL}{}^{0.25}\right]$$

$$We_{SG} = \frac{\rho_G v_{SG}{}^2 d}{\sigma}\left(\frac{\rho_L-\rho_G}{\rho_G}\right)^{1/3} \qquad \mathrm{Re}_{SL} = \frac{\rho_L v_{SL} d}{\mu_L}$$

Vertical Flow …

- **Okawa et al. (2002)**

$$R_E = \Gamma\left(\frac{\tau_I\delta}{\sigma}\right) = k_E \rho_L \frac{\tau_I\delta}{\sigma}\left(\frac{\rho_L}{\rho_G}\right)^n \qquad \mathrm{R}_D = k_D C = k_D \frac{\rho_L F_E v_{SL}}{V_{SG}}$$

$$F_E = \frac{k_E}{k_D}\frac{f_I \rho_G v_{SG}{}^3 \delta}{v_{SL}\sigma}\left(\frac{\rho_L}{\rho_G}\right)^n$$

- **Schadel (1988)**

$$F_E = \frac{W_L - W_{Lc}}{W_L} - \frac{R_{D,\max}}{W_L\tilde{\mu}}\left(1\text{-}\exp(F_E\tilde{C})\right)$$

$$\tilde{\mu} = \frac{k_A v_{SG}\sqrt{\rho_L\rho_G}}{\pi d}$$

$$\tilde{C} = -\frac{4W_L}{C_{Max} v_{SG}\pi d^2}$$

Horizontal Flow

- **Paleev and Filipovich (1966)**

$$F_E = 0.015 + 0.44\log\left[\frac{\rho_C}{\rho_L}\left(\frac{\mu_L v_{SG}}{\sigma}\right)^2 \times 10^4\right] \qquad \rho_C = \rho_G\left(1+\frac{F_E v_{SL}\rho_L}{v_{SG}\rho_G}\right)$$

- **Williams (1990) Horizontal Stratified Flow**

$$\frac{F_E}{F_{E,Max}} = \frac{1.5\pi\frac{k_E}{4k_D}d(1-2\delta)\sqrt{\rho_G\rho_L}\,v_{SG}{}^4\,\frac{d}{S_i^*}}{1+1.5\pi\frac{k_E}{4k_D}d(1-2\delta)\sqrt{\rho_G\rho_L}\,v_{SG}{}^4\,\frac{d}{S_i^*}}$$

Inclined Flow

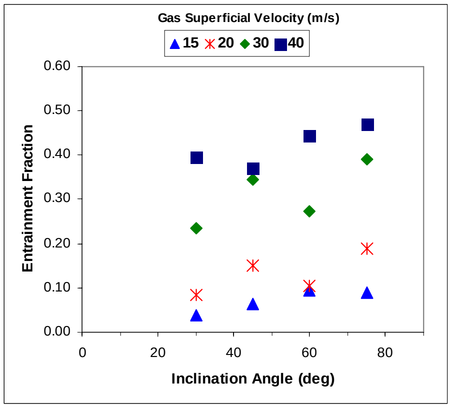
- **Ousaka et al. (1996)**
  - **Only Inclination Entrainment Data Measured**
  - **1 inch Pipe, Air/Water Fluid**
  - **Adapted Ishii and Mishima Vertical Flow Entrainment Correlation for Inclined Flow Based on 60 Data Points**

$$F_E = \tanh\left[(4\theta+3)\times 10^{-7}\,We_{SG}{}^{1.25}\left(\frac{\rho_L-\rho_G}{\rho_G}\right)^{\frac{1.25}{3}}\mathrm{Re}_{SL}{}^{0.25}\right]$$

Inclined Flow …

- **Ousaka et al. (1996)**

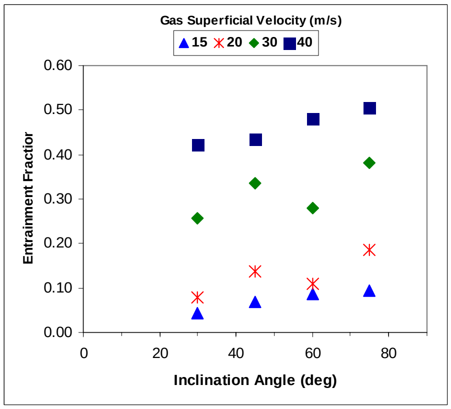
v_{SL} = 0.06 m/s



Inclined Flow …

- **Ousaka et al. (1996)**

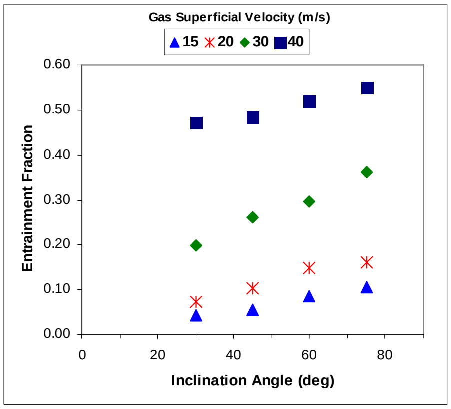
v_{SL} = 0.10 m/s



Inclined Flow …

- **Ousaka et al. (1996)**

v_{SL} = 0.20 m/s



Inclined Flow …

- **Chen (2005b)**

<u>Droplet Atomization</u>

$$R_E = \Gamma(\tau_i \delta / \sigma)$$

- Assuming Film Thickness << Pipe ID

$$\delta = (1 - F_E) v_{SL} d / (4 v_F)$$

$$\tau_i = \tfrac{1}{2} f_i \rho_G (v_C - v_F)^2$$

$$R_E = k_E \rho_L \frac{f_i \rho_G v_C{}^2 v_{SL} d (1 - F_E)}{8 \sigma v_F}$$

Inclined Flow …

- Chen (2005b)

  <u>Droplet Deposition</u>

  $$R_D = k_D C$$

  - **Uniform Droplet Distribution Across Pipe and No Slippage Between Gas and Drops Assumed**

  $$\left.\begin{aligned} C &= \rho_L F_{E,V} v_{SL} / v_C \\ R_D &= k_D \rho_L F_{E,V} v_{SL} / v_C \end{aligned}\right\} \mathit{Approximation}$$

Inclined Flow …

- Chen (2005b)

  $R_E = R_D$

  $$\frac{F_{E,V}}{1 - F_{E,V}} = k \frac{f_i \rho_G v_C (v_C - v_F)^2 d}{8 \sigma v_F}$$

  where $k = k_E / k_D$

  $$k = 1.5 \times 10^{-7} \, \mathrm{Re}_{SL} \left(\frac{\rho_G}{\rho_L} \right)^{0.15} \left(\frac{\mu_L}{\mu_G} \right)^{1.2}$$

Inclined Flow …

- Chen (2005b)
  - Asymmetric Distribution of Fluid in Horizontal and Inclined Flow
  - Average Film Thickness Corrected by Pipe Circumferential Wetted Fraction Θ

$$\frac{F_{E,H}}{1-F_{E,H}} = k\,\frac{f_i \rho_G v_C (v_C - v_F)^2 d}{8\sigma v_F \Theta} = k\psi$$

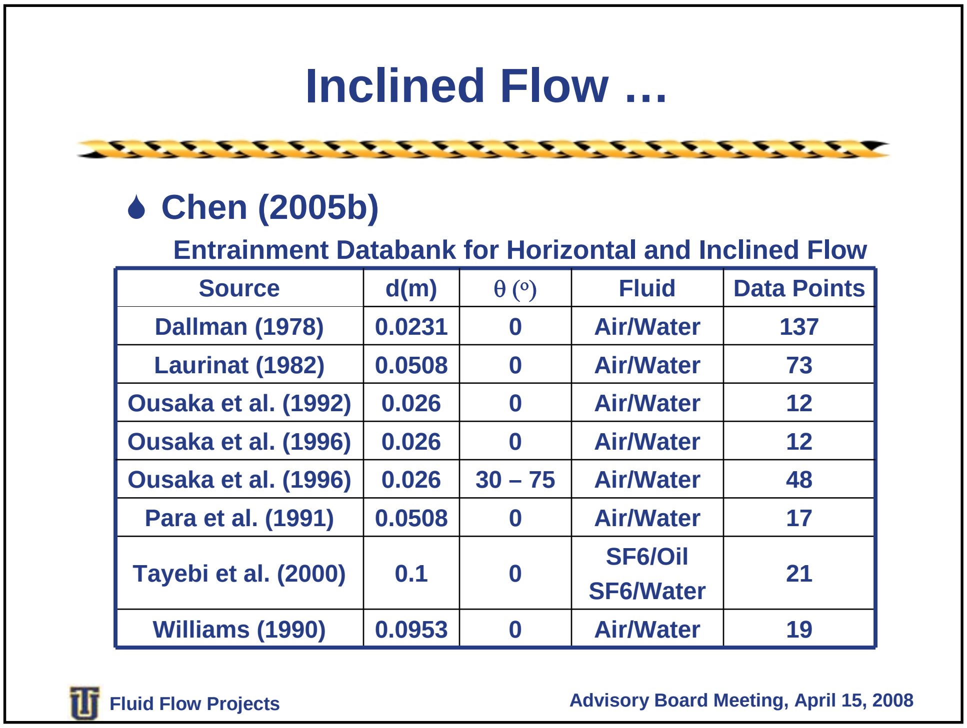
$$F_{E,H} = \frac{k\psi}{1+k\psi}$$

Inclined Flow …

- Chen (2005b)
  - Functionality of k_θ Determined by Trial-and-Error by Fitting Calculated F_E Against Experimental F_E

$$k_\theta = \exp\left(-0.036\,\frac{\mathrm{Re}_{LF}^{\;0.49}}{Fr_\theta} \right)$$

$$F_E = k_\theta\,\frac{k\psi}{1+k\psi}$$

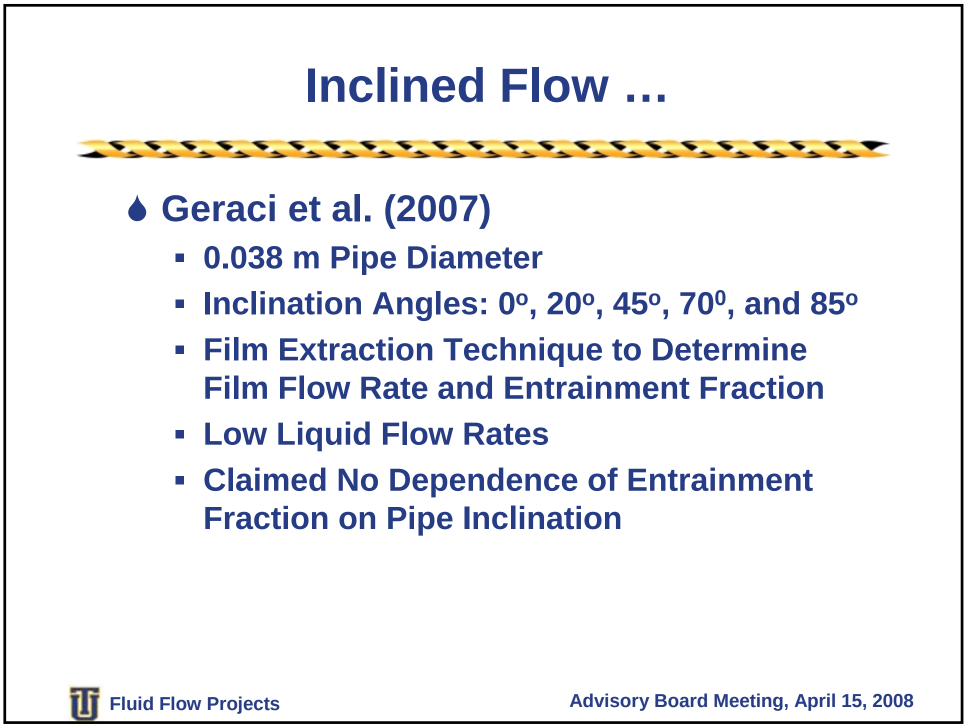


Inclined Flow …

- Chen (2005b)

Entrainment Databank for Horizontal and Inclined Flow

Source	d(m)	θ (^{o})	Fluid	Data Points
Dallman (1978)	0.0231	0	Air/Water	137
Laurinat (1982)	0.0508	0	Air/Water	73
Ousaka et al. (1992)	0.026	0	Air/Water	12
Ousaka et al. (1996)	0.026	0	Air/Water	12
Ousaka et al. (1996)	0.026	30 – 75	Air/Water	48
Para et al. (1991)	0.0508	0	Air/Water	17
Tayebi et al. (2000)	0.1	0	SF6/Oil SF6/Water	21
Williams (1990)	0.0953	0	Air/Water	19

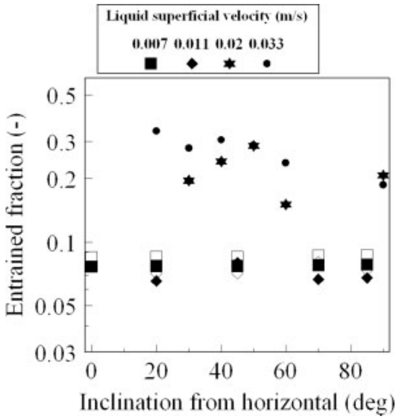


Inclined Flow …

- Geraci et al. (2007)
  - 0.038 m Pipe Diameter
  - Inclination Angles: 0^o, 20^o, 45^o, 70^0, and 85^o
  - Film Extraction Technique to Determine Film Flow Rate and Entrainment Fraction
  - Low Liquid Flow Rates
  - Claimed No Dependence of Entrainment Fraction on Pipe Inclination

Inclined Flow …

- Geraci et al. (2007)



Literature Review Summary

- Most Research and Models are for Vertical Annular Flow
- In Most Models, Empirical Constants are Implemented Based on Experimental Data
- Only 48 Entrainment Fraction Experimental Data Points for Inclined Flow
- Conflicting Results for Pipe Inclination Effect on Entrainment Fraction

Experimental Facility

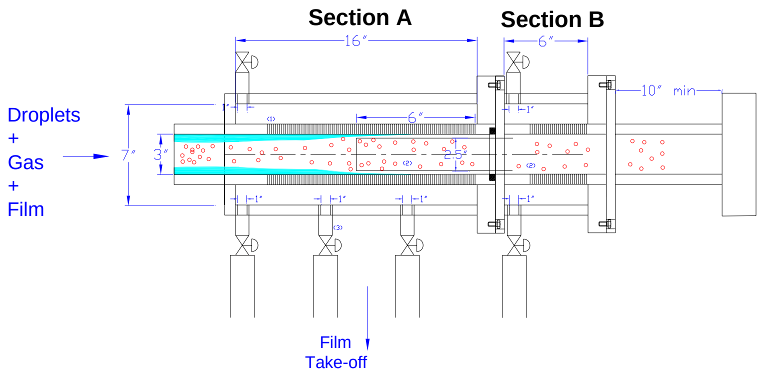
- 3 inch Severe Slugging Flow Loop

Experimental Facility

- Test Section 200 Diameters from Inlet to Ensure Fully Developed Flow
- Installation of Quick Closing Valves to Measure Local Liquid Holdup
- Conduct Tests at Horizontal and inclination angles from horizontal of 10^{o}, 20^{o}, 45^{o}, 75^{o}, and 90^{o}
- Measurement of Entrainment Fraction and Deposition Rate

Measurement Techniques

- Film Removal Device



Measurement Techniques

- Film Removal Device Section A
  - Measurement of Entrainment Fraction
  - Liquid Film is Removed Through Porous Section
  - Film Flow Rate will be Obtained
  - Entrainment Fraction will be Obtained:

$$F_E = 1 - \frac{q_{Film}}{q_{Liquid}}$$

Measurement Techniques

- Film Removal Device Section B
  - Measurement of Droplet Deposition Rate
  - Liquid Film is Removed Through Porous Section Similar to Section A
  - Film Volume will be Measured Over Time to Determine Deposition Rate

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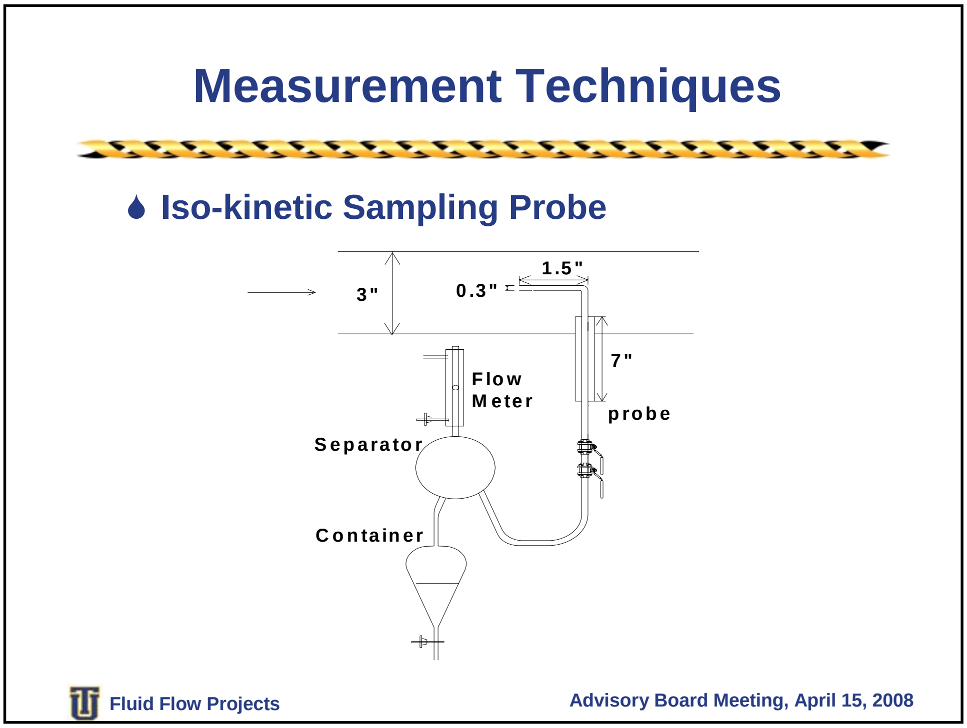
Measurement Techniques

- Iso-kinetic Sampling Probe
  - Entrained Droplets are Sampled Over a Given Length of Time at Various Radial Distances
  - Entrainment Flux Profile is Created
  - Entrainment Fraction is Calculated by Integrating Flux Profile
  - Most Accurate Under Low Liquid Flow Rates



Measurement Techniques

- Iso-kinetic Sampling Probe

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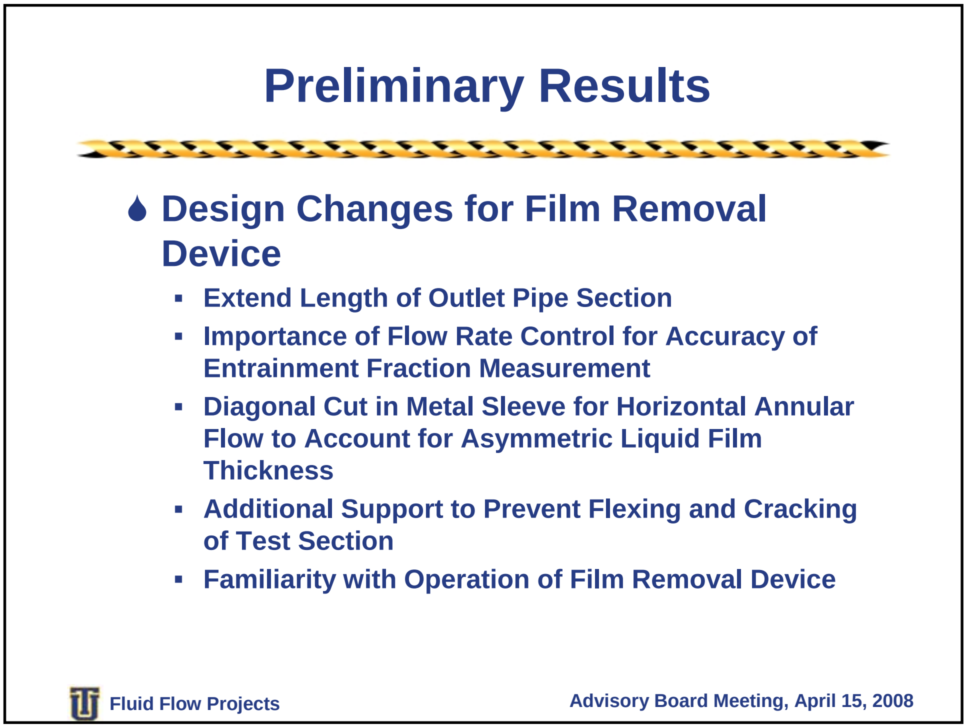

Preliminary Results

- Design Changes for Film Removal Device
  - Extend Length of Outlet Pipe Section
  - Importance of Flow Rate Control for Accuracy of Entrainment Fraction Measurement
  - Diagonal Cut in Metal Sleeve for Horizontal Annular Flow to Account for Asymmetric Liquid Film Thickness
  - Additional Support to Prevent Flexing and Cracking of Test Section
  - Familiarity with Operation of Film Removal Device

Fluid Flow Projects

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Summary

- More Accurate Entrainment Fraction Data Is Needed for Inclined Pipes
- Validation of Models is Needed for Entrainment Fraction in Inclined Pipes
- More Accurate Entrainment Fraction Model is Needed for Inclined Pipes

Future Tasks

- Fabrication of Film Removal Device
- Facility Modifications
- Acquire Entrainment Data for Various Flow Rates and Inclination Angles
- Validate Existing Models with Experimental Data

Project Schedule

♦ Literature Review	Ongoing
♦ Facility Construction	May 2008
♦ Data Acquisition	August 2008
♦ Model Comparison	December 2008
♦ Final Report	May 2009

Questions/Comments

?

Liquid Entrainment in Annular Two-Phase Flow in Inclined Pipes

Kyle Magrini

PROJECTED COMPLETION DATES:

Literature Review	Completed
Facility Modifications	May 2008
Testing	August 2008
Model and Correlation Validation	January 2009
Final Report	May 2009

Objectives

The objectives of this study are:

- to acquire entrainment data in two-phase gas-water annular flow through pipes from horizontal to near vertical,
- to validate current correlations and models with experimental results,
- to improve current models, if necessary, with new correlations, or develop a new model.

Introduction

Annular flow usually occurs at high gas velocities and low to medium liquid velocities. The liquid flows as a film along the wall of the pipe and as droplets entrained in the gas core. The interface between the gas core and liquid film is usually very wavy, causing atomization and deposition of liquid droplets. Under equilibrium conditions, the rate at which the droplets atomize and deposit becomes equal, resulting in a steady fraction of the liquid being entrained as droplets, F_E. This critical parameter is crucial to understand and model the behavior of annular flow.

Most multiphase flow prediction models (including the TUFFP unified mechanistic models) are based on a simplified (one-dimensional) two-fluid model in which empirical closure relationships (i.e. interfacial friction factor, interfacial area, droplet entrainment fraction, etc.) are needed. The performance of the multiphase flow model is determined by the accuracy and physical completeness of these closure relationships. The literature reveals that sufficient physics of multiphase flow may not be contained in these empirical closure relationships. Therefore, further refinements of these closure relationships can significantly improve the performance of multiphase mechanistic models.

Chen (2005a) conducted a sensitivity study to investigate the influence of individual closure relationships on the predictions of a multiphase mechanistic model. The study showed that in annular flow the variation in droplet entrainment fraction can substantially affect the predicted pressure gradient and liquid hold-up. Thus, the use of an accurate predictive model for entrainment fraction is imperative.

Literature Review

The liquid droplet entrainment phenomenon is very complicated. Various factors, such as pipe size, pipe orientation, velocity, and fluid properties, control the process. There are several studies devoted to understanding the different aspects of liquid entrainment. The majority of the studies on liquid entrainment are dedicated to vertical annular flow where a symmetrical film thickness usually exists. Many correlations and models have been developed for entrainment in vertical annular flow. However, for horizontal annular flow, investigations are limited to a few correlations, and for inclined annular flow, studies rarely are present in the literature.

Vertical Flow Correlations

Wallis (1968) proposed the empirical correlation,

$$F_E = 1 - \exp\left[-0.125 \times \left(10^4 \frac{v_{SG}\mu_G}{\sigma}\sqrt{\frac{\rho_G}{\rho_L}} - 1.5\right)\right]. \qquad (1)$$

Dallman (1978) derived an empirical correlation for entrainment fraction by balancing the droplet entrainment, R$_E$, and deposition, R$_D$, rates assuming equilibrium flow. Dallman determined the atomization rate to be

$$R_A = k_E\left(\frac{W_L - W_{Lc}}{\pi d}\right) v_{SG}{}^2 \sqrt{\rho_G \rho_L}\ , \tag{2}$$

where W$_{Lc}$ is the critical liquid flow rate below which no entrainment occurs. Using the turbulence diffusion equation, Dallman determined the droplet deposition rate as

$$R_D = k_D C\ , \tag{3}$$

where C is the droplet concentration. Assuming negligible slippage between the gas phase and droplets, the final form of Dallman's correlation is

$$\frac{F_E}{F_{E\max}} = \frac{\dfrac{k_E}{4k_D}\, d\sqrt{\rho_G \rho_L}\, v_{SG}{}^3}{1 + \dfrac{k_E}{4k_D}\, d\sqrt{\rho_G \rho_L}\, v_{SG}{}^3}\ , \tag{4}$$

where the maximum entrainment possible, F$_{E,max}$, is defined as

$$F_{E\max} = 1 - \frac{W_{Lc}}{W_L}\ . \tag{5}$$

The coefficients of Dallman's correlation, k_E, k_D, and F$_{E,max}$, are case dependent. Laurinat (1982) and Asali (1984) implemented similar formulations as Eq. (4).

Schadel (1988) correlated the droplet deposition rate as

$$R_D = R_{D\max}\left(1 - \exp\left(-\frac{C}{C_{\max}}\right)\right). \tag{6}$$

From this equation, Schadel developed the following correlation for entrainment

$$F_E = \frac{W_L - W_{Lc}}{W_L} - \frac{R_{D\max}}{W_L \tilde{\mu}}\left(1 - \exp(F_E \tilde{C}\right), \tag{7}$$

where $\tilde{\mu} = \dfrac{k_E v_{SG} \sqrt{\rho_G \rho_L}}{\pi d}$

and $\tilde{C} = -\dfrac{4W_L}{C_{\max} v_{SG} \pi d^2}$

Schadel fit data sets to determine values for R$_{Dmax}$, C$_{max}$, and k$_A$.

Oliemans et al. (1986) correlated vertical annular flow data from the HARWELL data bank and determined the following expression

$$\frac{F_E}{1-F_E} = 10^{-2.52} \rho_L{}^{1.08} \rho_G{}^{0.18} \mu_L{}^{0.27} \mu_G{}^{0.28} \times \sigma^{-1.8} d^{1.72} v_{SL}{}^{0.7} v_{SG}{}^{1.44} g^{0.46}\ . \tag{8}$$

A modified Oliemans et al. correlation is used in the TUFFP unified mechanistic model for entrainment fraction calculation.

Ishii and Mishima (1989) correlated vertical annular flow data sets of entrainment and derived the following correlation based on the Weber number of the gas phase and the Reynolds number of the liquid,

$$F_E = \tanh\left[7.25\times10^{-7} We_{SG}{}^{1.25}\left(\frac{\rho_L - \rho_G}{\rho_L}\right)^{\frac{1.25}{3}} \mathrm{Re}_{SL}{}^{0.25}\right] \tag{9}$$

where

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

and

$$\mathrm{Re}_{SL} = \frac{\rho_L v_{SL} d}{\mu_L}\cdot$$

Zuber (1962) and Hutchinson and Whalley (1973) argued that sufficient shear stress at the gas-liquid interface to overcome the resistance of the surface tension was the primary effect related to droplet formation and entrainment. From this concept, Hutchinson and Whalley suggested the following relationship at quasi-equilibrium between the deposition rate and shear stress and surface tension,

$$R_E = R_D = k_D C = \Gamma\left(\frac{\tau_i \delta}{\sigma}\right)\cdot \tag{10}$$

Based on the relationship in Eq. (10), Okawa et al. (2002) suggested that

$$R_E = k_E \rho_L \frac{f_I \rho_G v_{SG}{}^2 \delta}{\sigma}\left(\frac{\rho_L}{\rho_G}\right)^{0.2}. \tag{11}$$

Balancing the deposition and entrainment rates for quasi-equilibrium yields

$$F_E = \frac{k_E}{k_D}\frac{f_I \rho_G {v_{SG}}^2 \delta}{v_{SL}\sigma}\left(\frac{\rho_L}{\rho_G}\right)^{0.2}. \qquad (12)$$

After assuming superficial gas velocity approximately equal to actual gas velocity and the shear stress at the wall approximately equal to the shear at the interface, Okawa et al. proposed the final form of their entrainment correlation,

$$\frac{F_E}{1-F_E} = \frac{k_A}{4k_D}\frac{\sqrt{f_I f_w}\sqrt{\rho_G \rho_L}{v_{SG}}^2\delta}{\sigma}\left(\frac{\rho_L}{\rho_G}\right)^{0.2}. \qquad (13)$$

Okawa et al. developed an empirical correlation for the empirical constant k_E by fitting data to Eq. (13). However, lack of a reliable correlation for k_D limits the applicability of this correlation. Sugawara (1990) developed a similar correlation.

Horizontal Flow Correlations

For horizontal flow, gravitational forces may play a much more significant role during the deposition process compared to vertical flow. Asymmetrical film thickness and asymmetric droplet distribution in the gas phase add complexity to an already difficult prediction problem. Therefore, there are few horizontal correlations found in the literature.

Paleev and Filipovich (1966) developed an empirical correlation based on data sets of entrainment for a horizontal duct,

$$F_E = 0.015 + 0.441\log\left[\frac{\rho_C}{\rho_L}\left(\frac{\mu_L v_{SG}}{\sigma}\right)^2 \times 10^4\right], \qquad (14)$$

where ρ_C is the mixture density of the core, defined as

$$\rho_C = \rho_G\left(1+\frac{F_E v_{SL}\rho_L}{v_{SG}\rho_G}\right). \qquad (15)$$

Williams (1990) derived a model for horizontal stratified flow using an approach similar to that of Dallman (1978),

$$\frac{F_E}{1-\frac{W_{Lc}}{W_L}} = \frac{1.5\pi\frac{k_E}{4k_D}d(1-2\delta)\sqrt{\rho_G\rho_L}{v_{SG}}^4\frac{d}{{S_I}^*}}{1+1.5\pi\frac{k_E}{4k_D}d(1-2\delta)\sqrt{\rho_G\rho_L}{v_{SG}}^4\frac{d}{{S_I}^*}}, \qquad (16)$$

where S_I^* is the interfacial perimeter assuming ideal stratified flow. This correlation can be perceived as the first effort to take into account asymmetric effects of the liquid film on entrainment fraction.

Inclined Flow Correlations

Ousaka et al. (1996) conducted air/water annular flow experiments in a 1-in. diameter pipe. This study presents the only extensive entrainment data in inclined pipes found in the literature. Therefore, most correlations and models for inclined annular flow entrainment are derived from the Ousaka et al. data set. Figures 1-3 show Ousaka's experimental results of entrainment fraction for varying inclination angles and gas/liquid flow rates. Adapting the Ishii and Mishima (1989) correlation for vertical annular flow, Ousaka et al. determined the following correlation for inclined annular flow based on the inclination angle (θ),

$$F_E = \tanh\left[(4\theta+3)\times10^{-7}{We_G}^{1.25}\left(\frac{\rho_L-\rho_G}{\rho_L}\right)^{\frac{1.25}{3}}{\mathrm{Re}_L}^{0.25}\right]. \qquad (17)$$

Chen (2005b) developed a correlation for annular flow entrainment for all angles. He used the approach employed by Okawa et al. (2002), developing the relationship for entrainment rate as

$$R_E \sim \Gamma\left(\frac{\tau_i l}{\sigma}\right) = k_E \rho_L \frac{\tau_i \delta}{\sigma}, \qquad (18)$$

where l is the characteristic length defined as the liquid film thickness, δ. In Chen's model, k_E is the coefficient of entrainment rate, and τ_I is the interfacial shear stress defined as

$$\tau_I = \frac{1}{2} f_I \rho_G (v_C - v_F)^2 .$$

Thus, the entrainment rate is defined as

$$R_E = k_E \rho_L \frac{f_I \rho_G (v_C - v_F)^2 \delta}{2\sigma} . \tag{19}$$

Chen first developed his correlation for vertical annular flow. The liquid film thickness in vertical flow is

$$\delta = \frac{(1-F_E) v_{SL} d}{4 v_F} . \tag{20}$$

Combining Eqs. (19) and (20) yields

$$R_E = k_E \rho_L \frac{f_I \rho_G {v_C}^2 v_{SL} d (1-F_E)}{8 \sigma v_F} . \tag{21}$$

Assuming uniform droplet distribution across the pipe cross-section and no slippage between the gas phase and entrained droplets, the droplet concentration can be approximated as

$$C = \rho_L \frac{F_E v_{SL}}{v_C} . \tag{22}$$

Therefore,

$$R_D = k_D \rho_L \frac{F_E v_{SL}}{v_C} . \tag{23}$$

Assuming quasi-equilibrium and balancing the deposition and entrainment rates, entrainment fraction for vertical flow is determined by

$$\frac{F_E}{1-F_E} = k \frac{f_I \rho_G {v_C}^2 (v_C - v_F)^2 d}{8 \sigma v_F} , \tag{24}$$

where $k = k_E / k_D$.

Chen used the vertical annular flow data sets listed in Table 1 to correlate the coefficient k in Eq. (24) as

$$k = 1.5 \times 10^{-7} \operatorname{Re}_{SL} \left(\frac{\rho_G}{\rho_L} \right)^{0.15} \left(\frac{\mu_L}{\mu_G} \right)^{1.2} . \tag{25}$$

After deriving the correlation for vertical annular flow, Chen adapted the correlation for horizontal and inclined annular flows by accounting for the effects of gravity. To account for the asymmetric distribution of the liquid film, the calculation of the average film thickness is corrected by the pipe circumferential wetted fraction (Θ). This parameter is predicted by using the Grolman correlation (1994). The liquid film thickness is modified from Eq. (20) and becomes

$$\delta = \frac{(1-F_E) v_{SL} d}{4 v_F \Theta} . \tag{26}$$

Therefore, Eq. (24) is modified for horizontal and inclined annular flow to be

$$\frac{F_E}{1-F_E} = k \frac{f_I \rho_G v_C (v_C - v_F)^2 d}{8 \sigma v_F \Theta} . \tag{27}$$

The gravitational force also promotes settling of entrained droplets to the liquid film. Chen proposed the use of a correction factor, known as the "inclination angle factor" (k_θ), to account for this gravitational settling effect. He argued that k_θ must at least be a function of a modified Froude number, Fr_θ, which he defined as

$$Fr_\theta = \sqrt{\frac{\rho_G {v_{SG}}^2}{(\rho_L - \rho_G) g d \cos\theta}} . \tag{28}$$

Chen attempted to incorporate k_θ into the deposition rate R_D with no success. Instead, k_θ is applied to the predictions given by Eq. (27) to obtain the entrainment fraction for horizontal and inclined flow. Using the data sets in Table 2, k_θ is correlated by

$$k_\theta = \exp\left(-0.036\frac{\mathrm{Re}_{LF}^{\ 0.49}}{Fr_\theta}\right), \tag{29}$$

where Re_{LF} is the Reynolds number of the liquid film defined as

$$\mathrm{Re}_{LF} = \frac{\rho_L v_F \delta}{\mu_L}. \tag{30}$$

The final form of the entrainment fraction for horizontal and inclined flow is given by

$$F_E = k_\theta \frac{k\psi}{1+k\psi}, \tag{31}$$

where

$$\psi = \frac{f_I \rho_G v_c (v_C - v_F)^2 d}{8\sigma v_F \Theta}.$$

For vertical annular flow, it is clear that k_θ and Θ are equal to 1, so that Eq. (31) is equivalent to Eq. (24).

Paras and Karabeas (1991) found that the drop concentration decreasing from the interface to the bulk. Pan and Hanratty (2002) showed an exponential decay of droplet concentration from the bottom to the top. Based on these experiments, Al-Sarkhi (2007) stated that the assumption of a uniform distribution of droplets in the gas core is not reasonable in Chen's model. Al-Sarkhi also questioned scaling up entrainment data sets from small pipe diameters and extrapolating or interpolating the whole range of inclination angles based on a single experiment conducted by Ousaka et al. that includes only 48 data sets at four inclination angles.

Azzopardi (2007) performed annular flow entrainment measurements for inclined flow in a 1.5-in. diameter pipe. A film extraction technique was used to determine liquid film flow rate and entrainment fraction. Azzopardi noted that for the flow rates studied, the entrainment fraction was only very slightly influenced by pipe inclination. This effect can be seen in Fig. 4. Azzopardi proposed that as the inclination angle increases, the film thickness at the bottom decreases, but the wave activity of the film increases. The combination of these two trends may balance out, resulting in the near insensitivity of entrainment fraction to pipe inclination.

Experimental Study

TUFFP's 76.2-mm (3-in.) diameter severe slugging facility (shown in Fig. 5) will be modified for this experimental study. The facility is capable of being inclined from horizontal to vertical. Pressure and temperature transducers will be placed near the test section to obtain fluid properties and flowing characteristics that are used in several of the entrainment fraction correlations. Quick-closing valves will be installed on the facility to measure the local liquid holdup of the flow.

The test section used to obtain entrainment fraction will be placed 200d (15.24 m) from the entrance to ensure fully developed flow. Experiments for entrainment fraction will be conducted at inclination angles from horizontal of 0^o, 10^o, 20^o, 45^o, 75 and 90^o. Two methods will be used to calculate the entrainment fraction.

Test Fluids

Compressed air and Tulsa city tap water will be used in this study.

Film Removal Device

The procedure for measuring entrainment fraction in the test section involves removing the liquid film from the wall of the pipe while allowing the gas phase entrained with droplets to continue to flow. The entrained liquid flow rate will be calculated by subtracting the liquid film flow rate from the total liquid flow rate. The specially designed test section is shown in Fig. 6 Section A and is similar to the one used by Hay et al. (1996), Azzopardi et al. (1996), Simmons and Hanratty (2001), and Al-Sarkhi and Hanratty (2002). The flow passes through a porous section and the liquid film, traveling at a lower velocity than the gas core, is pushed through the porous section. The high inertia of the droplets in the gas core flowing close to the gas velocity prevents them from being removed through the porous section. To ensure no droplets will escape, a long sleeve will be inserted close to where the liquid film dissipates. This sleeve will be moved in and out in the pipe to make sure the liquid film passes under the sleeve and only the gas core passes through the test section. The film take off rate will be controlled by valves.

The deposition rate will also be measured after the liquid film is stripped in Section A of the test section. In Section B of Fig. 6, the film will once again be stripped from the flow through a porous section. The deposition rate of the droplets will be calculated based on the film flow measured.

Iso-kinetic Sampling Probe

An iso-kinetic sampling probe (shown in Fig. 7) will also be used in the facility to measure entrainment fraction. The iso-kinetic sampling probe will be inserted into the pipe at various radial distances. The liquid sampled from the gas core will be separated in a small gas-liquid separator and collected in a graduated cylinder. From these measurements, the droplet entrainment flux profile will be determined. The entrainment fraction can be calculated by integrating this flux profile. The iso-kinetic sampling probe works best under low liquid flow rates where a more distinct division between the gas core and liquid film exists. The results of the iso-kinetic sampling probe will be used in validating the results obtained from the film removal device.

Future Tasks

The main tasks for the future are:

- Complete the facility modifications,
- Conduct experiments,
- Validate correlations,
- Modify or develop new correlations

Nomenclature

C = droplet concentration [kg/m^3]

d = pipe diameter [m]

F_E = entrainment fraction

Fr = Froude number

k = empirical entrainment and deposition coefficients [m/s]

l = characteristic length [m]

R = entrainment and deposition rates [kg/m^{2}s]

Re = Reynolds number

S_I = interfacial perimeter [m]

S_I^* = ideally stratified interfacial perimeter [m]

v = velocity [m/s]

We = Weber number

Greek Letters

δ = liquid film thickness [m]

Γ = function indicator

Θ = wetted pipe circumferential fraction

μ = viscosity [kg/ms]

θ = pipe inclination angle [degree]

ρ = density [kg/m^3]

σ = surface tension [N/m]

τ = shear stress [N/m]

ψ = coefficient in entrainment correlation

Subscripts

C = gas core

c = critical

D = deposition

d = droplet

E = entrainment

F = liquid film

G = gas phase

I = interface

L = liquid phase

LF = liquid film

max = maximum

SG = superficial gas

SL = superficial liquid

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Source	d (m)	θ (°)	Fluid	Data Points
HARWELL	0.006 ~ 0.0318	90	Air/Water Steam/Water	728
Deryabina et al. (1989)	0.013 ~ 0.052	90	Air/Water	66
Fore and Dukler (1995)	0.0508	90	Air/Water	20
Owen et al. (1985)	0.03175	90	Air/Water	49
Schadel (1988)	0.0254 ~ 0.042	90	Air/Water	59

Table 1. Databank of Entrainment Fraction for Vertical Annular Flow

Source	d (m)	θ (°)	Fluid	Data Points
Dallman (1978)	0.0231	0	Air/Water	137
Laurinat (1982)	0.0508	0	Air/Water	73
Ousaka et al. (1992)	0.026	0	Air/Water	12
Ousaka et al. (1992)	0.026	0	Air/Water	12
Ousaka et al. (1992)	0.026	30 ~ 75	Air/Water	48
Paras et al. (1991)	0.0508	0	Air/Water	17
Tayebi et al. (2000)	0.1	0	SF6/Oil SF6/Water	21
Williams (1990)	0.0953	0	Air/Water	19

Table 2. Databank of Entrainment Fraction for Horizontal and Inclined Flow.

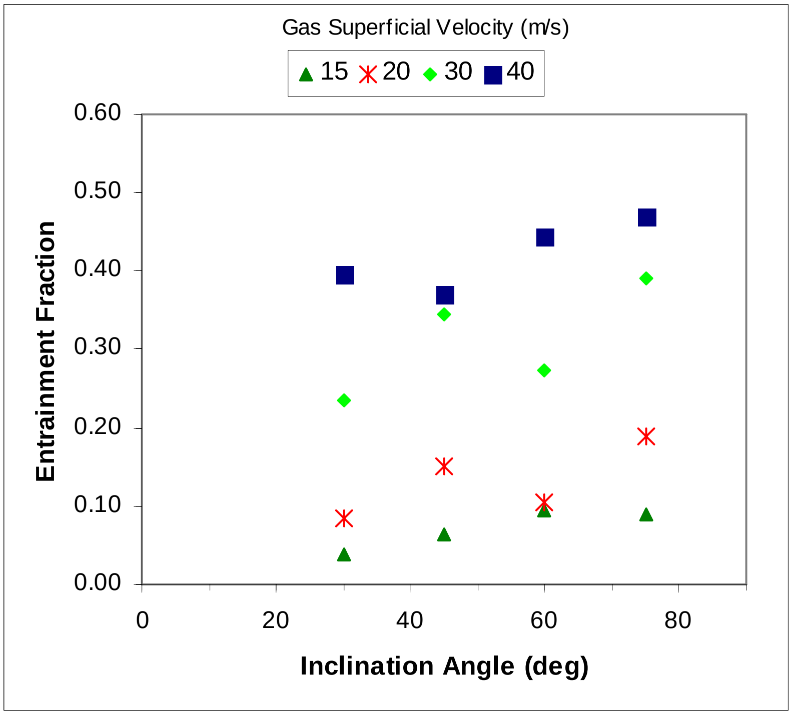


Figure 1. Ousaka et al. (1996) Entrainment fraction variation with inclination angle from horizontal. Superficial-liquid velocity = 0.06 m/s.

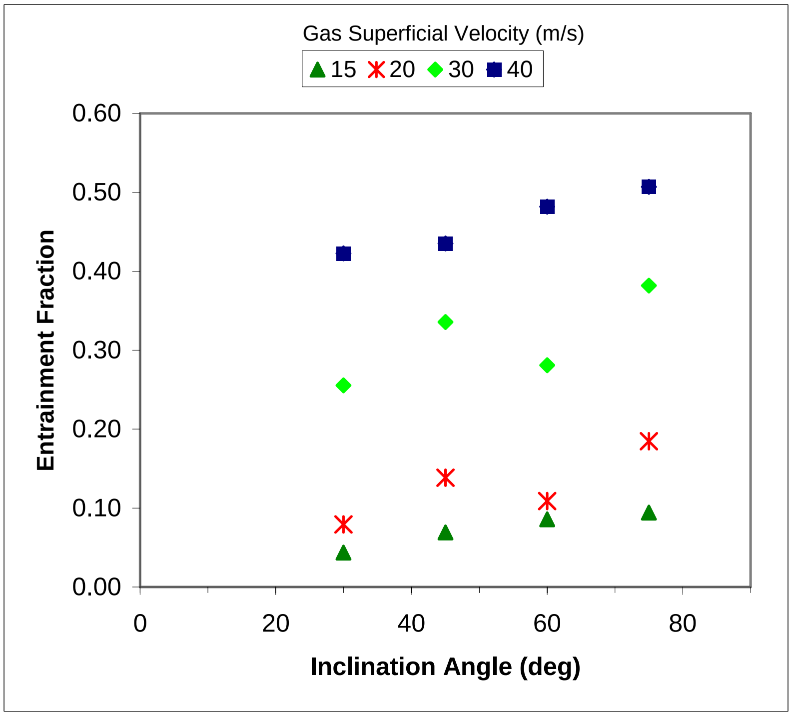


Figure 2. Ousaka et al. (1996) Entrainment fraction variation with inclination angle from horizontal. Superficial-liquid velocity = 0.1 m/s.

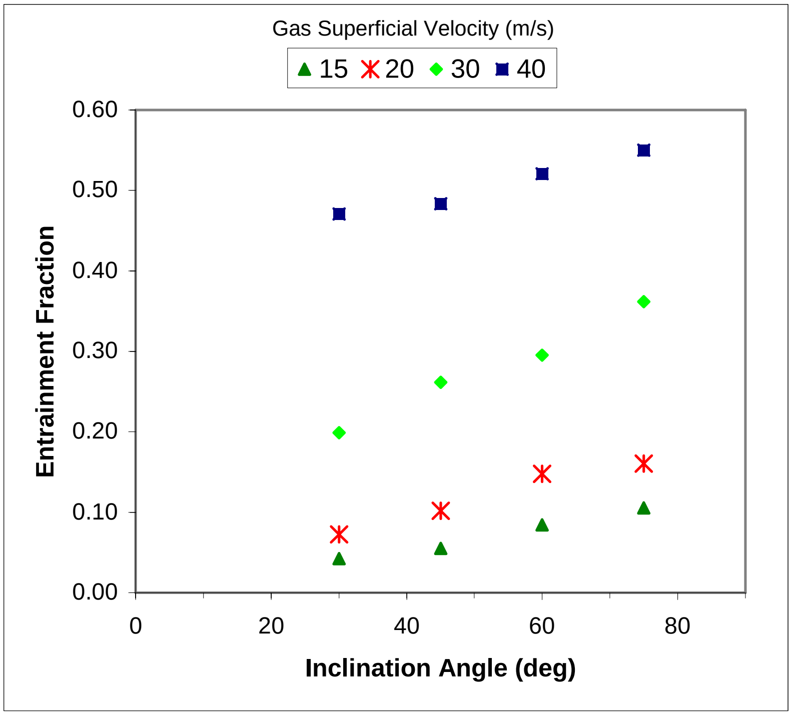


Figure 3. Ousaka et al. (1996) Entrainment fraction variation with inclination angle from horizontal. Superficial-liquid velocity = 0.2 m/s

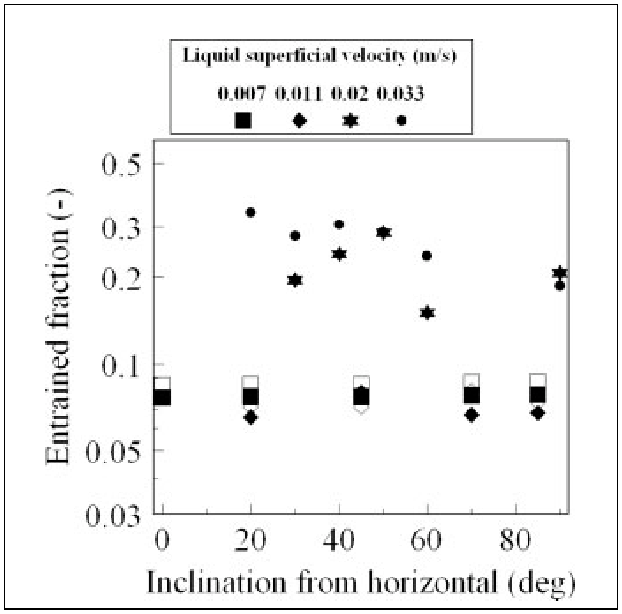


Figure 4. Azzopardi (2007) Entrained fraction variation with angle of inclination from horizontal. Open symbols: Superficial-gas velocity = 21.5 m/s; closed symbol: gas superficial velocity = 15 m/s. Data indicated by ●, ✶ are from Azzopardi et al. (1997): gas superficial velocity = 15 m/s.

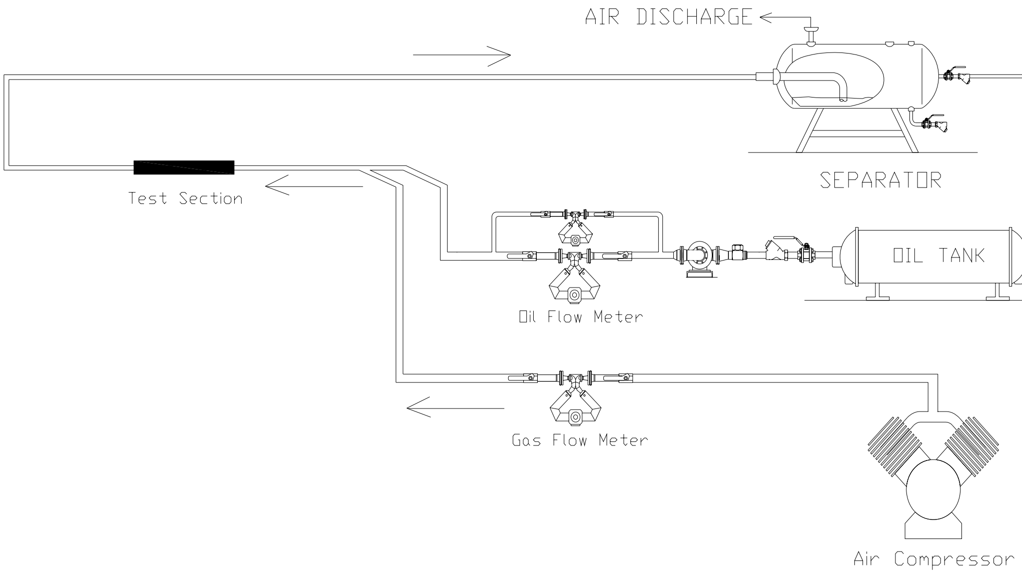


Figure 5. Facility Schematic

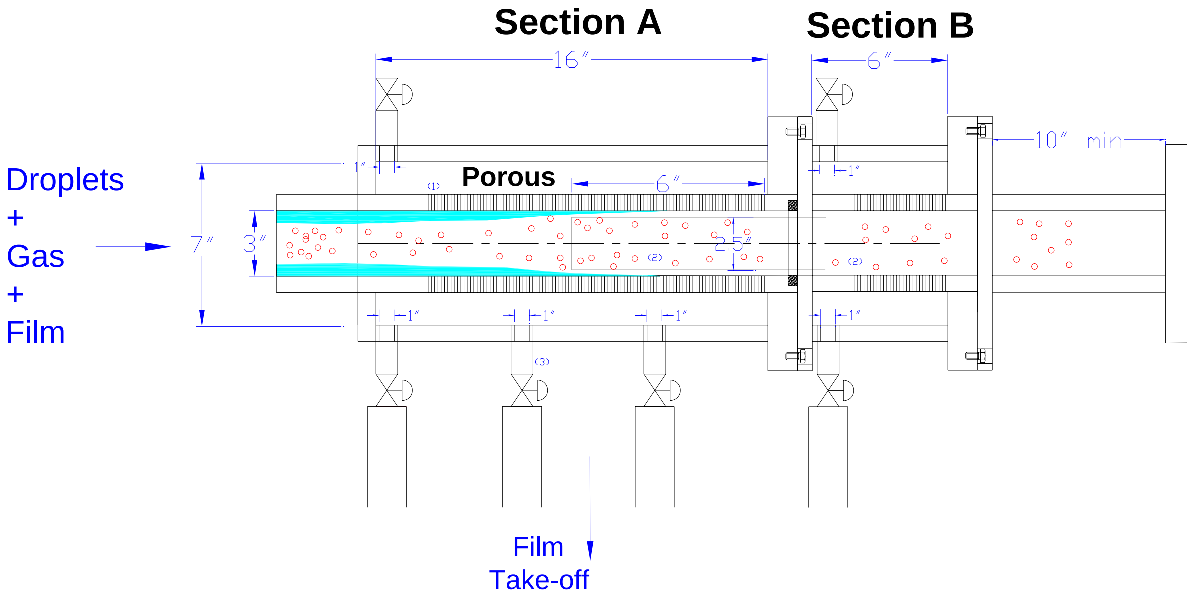


Figure 6. Film Removal Device

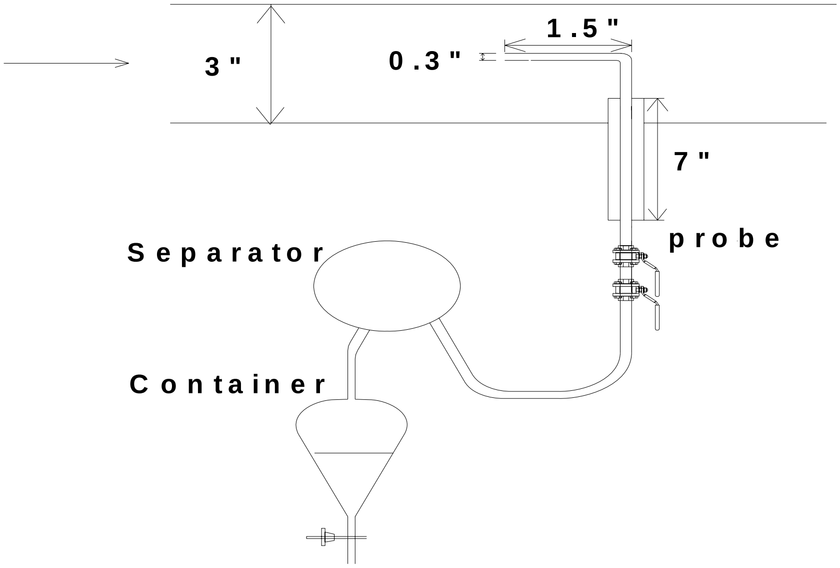


Figure 7. Iso-Kinetic Sampling System

Low Liquid Loading Flow

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

Low Liquid Loading Flow …

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

Low Liquid Loading Flow …

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

Low Liquid Loading Flow …

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

Low Liquid Loading Flow …

- Future Studies
  - Two and Three-phase, Large Diameter, High Pressure Horizontal and Inclined Flow
    - Requires New High Pressure Facility

Fluid Flow Projects

Three Phase Flow in Horizontal and Near Horizontal Pipelines with Low Liquid Loading – An Overview

Abdel Alsarkhi

Advisory Board Meeting, April 15, 2008

Outline

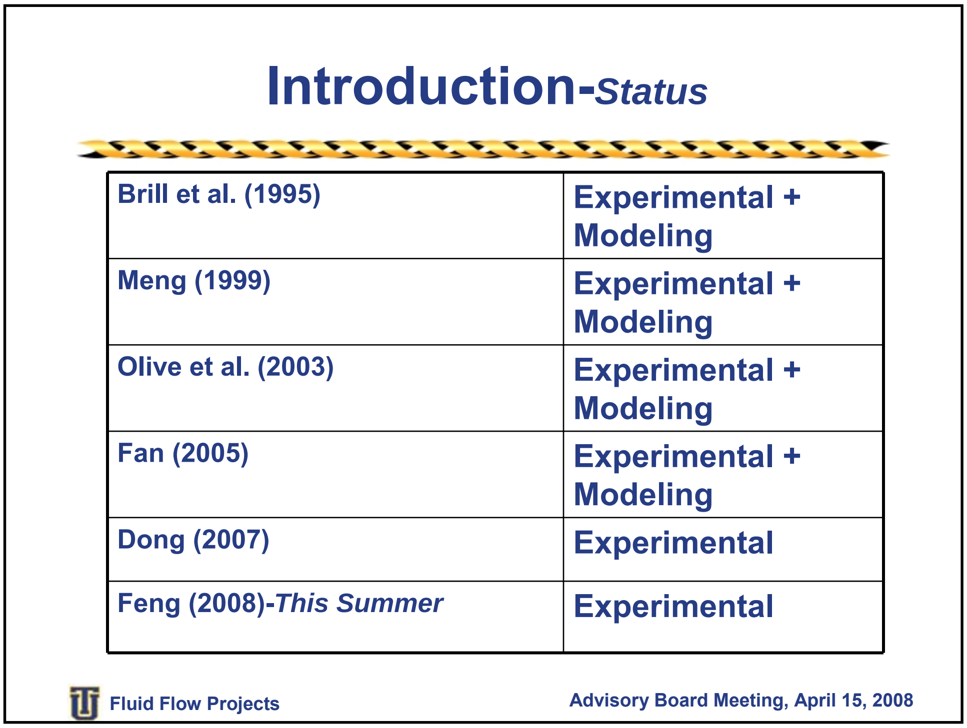
- Objectives
- Introduction and Status
- Literature Review
  - Experimental Studies & Milestones
  - Modeling Studies
- Achievements
- Future Work

Objectives

- Investigate Experimentally and Theoretically Behavior of Gas-Liquid Flow in Near-Horizontal Pipelines With Low Liquid Loadings

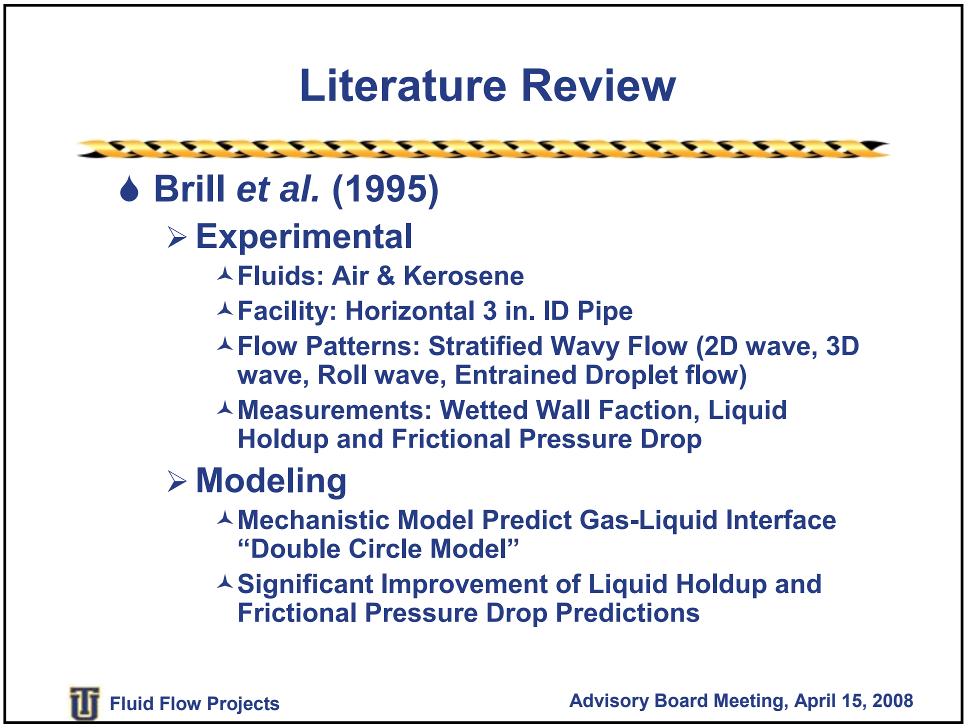
Introduction

- Frequently Encountered in Wet Gas Transportation
- Significant Increase in Pressure Loss Over That for Single-Phase Gas Flow
- Different Oil-Water Phase Distributions and Rheological Behaviors
- Efficiency of Corrosion Inhibitors is Strongly Related to Distribution of Liquids in the Pipeline
- Understanding of Flow Characteristics of Low Liquid Loading Flow is of Great Importance



Introduction-*Status*

Brill et al. (1995)	Experimental + Modeling
Meng (1999)	Experimental + Modeling
Olive et al. (2003)	Experimental + Modeling
Fan (2005)	Experimental + Modeling
Dong (2007)	Experimental
Feng (2008)-*This Summer*	Experimental



Literature Review

- Brill *et al.* (1995)
  - Experimental
    - Fluids: Air & Kerosene
    - Facility: Horizontal 3 in. ID Pipe
    - Flow Patterns: Stratified Wavy Flow (2D wave, 3D wave, Roll wave, Entrained Droplet flow)
    - Measurements: Wetted Wall Faction, Liquid Holdup and Frictional Pressure Drop
  - Modeling
    - Mechanistic Model Predict Gas-Liquid Interface “Double Circle Model”
    - Significant Improvement of Liquid Holdup and Frictional Pressure Drop Predictions

Literature Review …

- Meng (1999)
  - Experimental
    - Fluids: Air & Mineral Oil
    - Facility: Horizontal and Inclined (± 2°), 2 in. ID Pipe
    - Flow Patterns: Stratified and Annular
    - Measurements: Liquid Holdup; Frictional Pressure Drop, Droplet Entrainment Fraction, Deposition Rate, Liquid Film Thickness at Bottom, Liquid Film Flow Rate
  - Modeling
    - Two Fluid Model to Predict Liquid Holdup & Pressure Gradient
    - New Correlation for Interfacial Friction Factor

Literature Review …

- Olive *et al.* (2003)
  - Experimental
    - Fluids: Air & Water
    - Facility: Horizontal and Inclined (-1°), 2 in. ID Pipe
    - Flow Patterns: Stratified and Annular
    - Measurements: Liquid Holdup, Frictional Pressure Drop, Droplet Entrainment Fraction, Deposition Rate, Liquid Film Thickness at the Bottom, Liquid Film Flow rate
  - Comparison between Air-Oil (Meng, 1999) and Air-Water Data

Literature Review …

- Fan (2005)
  - Experimental-A
    - Fluids: Air & Water
    - Facility: Horizontal and Inclined (± 2°), 2 in. ID Pipe
    - Flow Patterns: Stratified Smooth & Wavy and Annular
  - Experimental-B
    - Fluids: Air & Water
    - Facility: Horizontal and Inclined (± 2°), 6 in. ID Pipe
    - Flow Pattern: Stratified Smooth & Wavy

Fluid Flow Projects

Advisory Board Meeting, April 15, 2008

Literature Review…

- Fan (2005) …
  - Measurements-A&B:
    - Pressure Gradient, Liquid Holdup, Wetted Wall Fraction, Entrainment Fraction (A: 2 in. only), Liquid Film Thickness, Interfacial Velocity
  - Modeling
    - Mechanistic Two Fluid Model with New Closure Relationships
    - New Correlations for Wetted Wall Fraction, Liquid-Wall Friction Factor, Interfacial Friction Factor

Fluid Flow Projects

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Literature Review…

- Dong (2007)
  - Experimental
    - Fluids: Air , Mineral Oil & Water
    - Facility: Horizontal 6 in. ID Pipe
    - Flow Patterns: 8 Different Stratified Flows
    - Measurements: Liquid Holdup, Frictional Pressure Drop, Droplet Entrainment Fraction, Wall Wetted Fraction, Liquid Film Thickness at the Bottom
  - Modeling
    - No Modeling Study
    - Comparisons with Fan, Zhang *et al*. (2003), Zhang and Sarica (2006) Models and OLGA Simulator

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Achievements

- Two/Three-Phase Flow Experiments
- Two/Three-phase Flow Modeling
  - Pressure Gradient
  - Liquid Holdup
  - Friction Factors Correlation
  - Wetted Wall Fraction Correlations
  - Droplet Entrainment and Deposition Effect on Interfacial Friction Factor (Meng)

Current Study

- **Feng (2008)-*Will be done this summer***
  - **Experimental**
    - Fluids: Air , Mineral Oil & Water
    - Facility: Horizontal (Higher v_{SG}), Inclined ± 2˚, 6 in. ID Pipe
    - Flow Pattern: Stratified Flow
    - Measurements: Liquid Holdup, Frictional Pressure Drop, Droplet Entrainment Fraction, Wall Wetted Fraction, Liquid Film Thickness at the Bottom
  - **Modeling**
    - No Modeling Study
    - Comparison with Dong, Fan, Zhang *et al*., Zhang and Sarica Models & OLGA Simulator

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Two/Three-phase Flows
Experiments-Data bank

TUFFP Low Liquid Loading Experimental Data Bank

Air-Liquid

- Horizontal, 3 in. ID, Air + Kerosene
- Horizontal and Inclined (±2), 2 in. ID, Air + Mineral Oil
- Horizontal and Inclined 2 in. ID, Air + Water
- Horizontal and Inclined, 6 in. ID, Air + Water

Air-Oil-Water

- Horizontal, 6 in. ID
- *Horizontal and Inclined, 6 in. ID (will be done this summer)*

Air-Oil-Water Flows Experiments

- Dong (2007)
  - Low Liquid Loading Gas-oil-water flow in Horizontal Pipes
  - 8 Flow Patterns within Stratified Flows
    - No Three Segregated Layers
    - No Fully Dispersed Single Layer
    - Different Oil Water Distribution Within Stratified Flow
  - Fan (2005) Model Gives Best Predictions of Pressure Gradient and Holdup

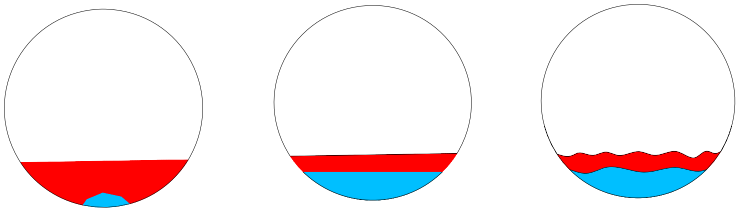
Example: Peculiar Flow Pattern (Dong)

- Stratified with Channel Water and Water in Oil Dispersion (STCW & DW/O)

Bottom View

v_{SG} = 10 m/s, LL = 300 $m^3/MMsm^3$, WC = 0.2

Air-Oil-Water Flow Patterns



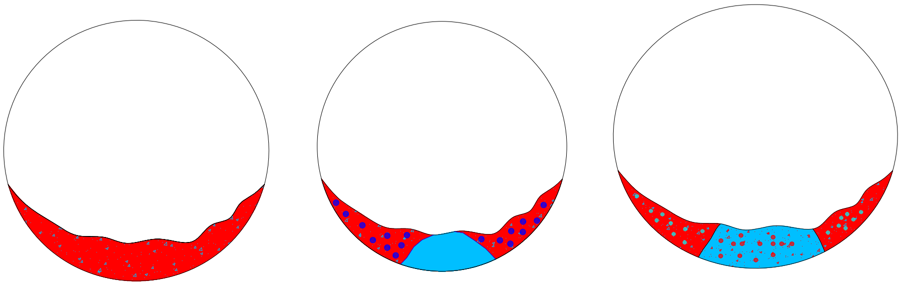
(a) SS – ODWS

(b) SS – ST

(c) SW – ST

☐ Air 🟥 Oil 🟦 Water

Air-Oil-Water Flow Patterns …



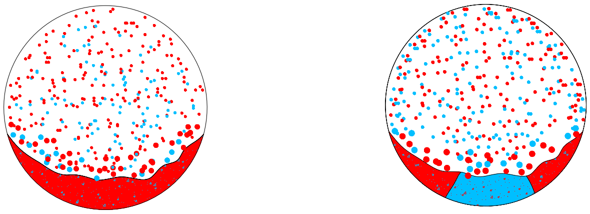
(d) SW – $D_{W/O}$

(e) SW – ST_{CW} & $D_{W/O}$

(f) SW – ST_{CW} & DD

☐ Air 🟥 Oil 🟦 Water

Air-Oil-Water Flow Patterns …



(g) SW & E – $D_{W/O}$

(h) SW & E – ST_{CW} & DD

☐ Air 🟥 Oil 🟦 Water

What is Missing?

- Ability To Predict Peculiar Flow pattern (Gas-Oil-Water)
- Annular Gas-oil-water Flows Experiments
- Entrainment Fraction Correlation/Model
  - Gas-oil-water
  - Gas-liquid
- Wetted Wall Fraction Correlation For Gas-oil-water Flow

What is Missing?...

- Interfacial Friction Factor Correlation For Gas-oil-water Flow
- Comparison Between Gas-oil-water And Gas-Liquid
  - Closure Relationships
  - Experimental Results For Horizontal and Near Horizontal
- Modeling of Low Liquid Loading Flow in R, θ, & Z- Direction
  - Short Section (CFD, FEA …)

Suggestions!

Fluid Flow Projects

Low Liquid Loading Gas-Oil-Water Flow in Near-Horizontal Pipes

Feng Xiao

Advisory Board Meeting, April 15, 2008

Outline

- Objectives
- Introduction
- TUFFP Low Liquid Loading Flow Studies
- Experiments
- Model Evaluation
- Project Schedule

Objectives

- Conduct Experimental Measurements and Observations
- Evaluate Unified Three-phase Model and Existing Correlations
- Modify Existing Correlations or Develop New Ones if Necessary

Introduction

- Low Liquid Loading Flows Correspond to Liquid to Gas Ratio ≤ 1100 $m^3/MMsm^3$
- It Exists Widely in Wet Gas Transmission Pipelines
- Small Amounts of Liquid Cause Significant Increase of Pressure Gradient and Other Problems

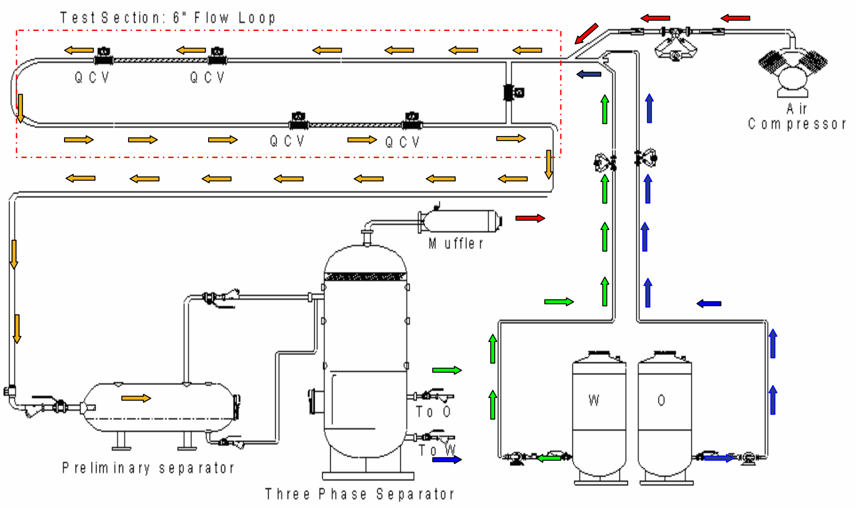
TUFFP Low Liquid Loading Flow Studies

- Low Liquid Loading Two-phase Pipe Flows
  - Chen (1997), Meng (1999): Air/Oil
  - Olive (2001), Fan (2005): Air/Water
- Low Liquid Loading Three-phase Pipe Flows
  - Dong (2007)
    - Air-oil-water, 0^{o}, 6-in ID Pipe
    - 156 Tests with up to 17.5-m/s V_{SG} and up to 0.038-m/s V_{SL}
    - Evaluated Fan's Model, Unified Three-phase Model and OLGA
    - Recommendations for Future Studies

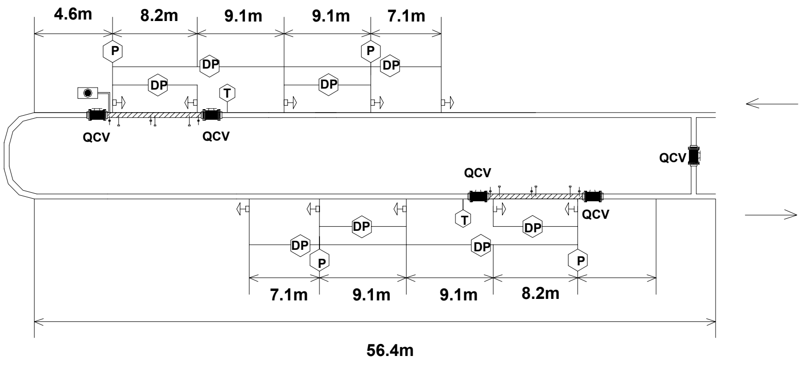
Experiments

- Experimental Facility and Flow Loop
- Instrumentation and Data Acquisition
- Working Fluids
- Test Ranges

Facility: Flow Loop



Facility: Test Section

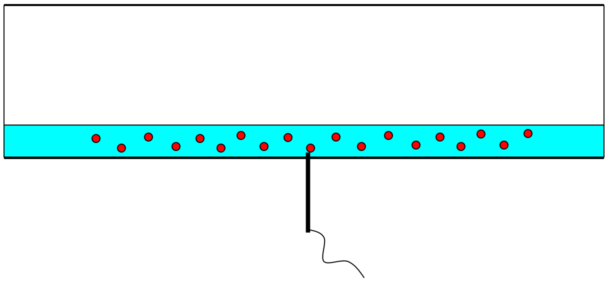


Instrumentation/Data Acquisition

- Pressure and Temperature : PTs and DPs and TTs
- Holdup: QCVs and Pigging System
- Wetted Wall Perimeter: Scales on Inner Wall
- Liquid Film Thickness: Conductivity Probes
- Liquid Velocity: Cold Liquid Injection
- Liquid Entrainment: Iso-kinetic Sampling System
- Cross-sectional Viewing System
- Data Acquisition: DeltaV

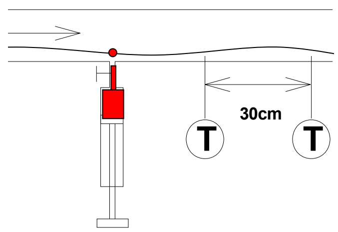
Film Thickness and Phase Continuity: Conductivity Probe

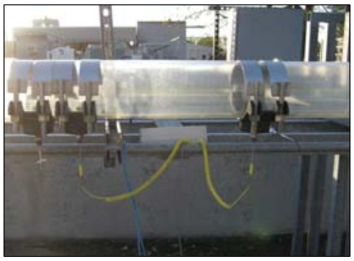
- Principle: Conductivity Difference



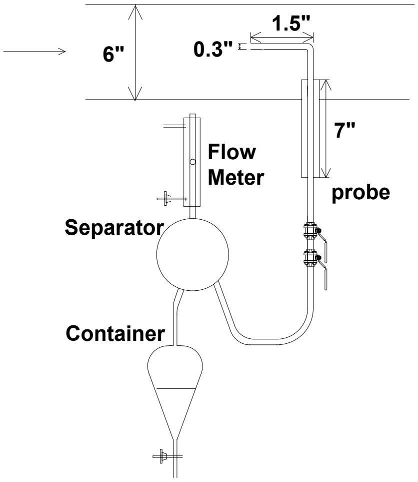
Film Velocity: Cold Liquid Injection

- Principle: Temperature Variation
- $\text{Velocity} = \dfrac{\text{Distance}}{\text{Time}}$

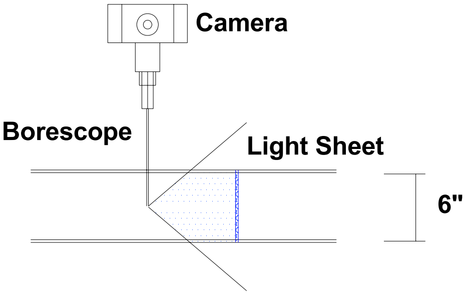


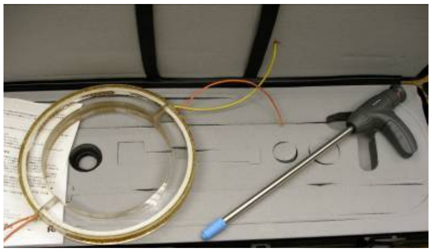


Liquid Entrainment: Iso-kinetic Sampling System



Interface Shape: Cross-sectional Viewing System





Test Fluids

- Tap Water/Mineral Oil/Air
- Oil Properties (Tulco Tech 80 Oil)
  - API Gravity: 33.2°
  - Density: 858.78 kg/m3 @ 15.6 °C (60 °F)
  - Viscosity: 13.5 cp @ 40 °C (104 °F)
  - Surface Tension (with Air): 29.14 dynes/cm @ 25.1 °C (77.2 °F)
  - Interfacial Tension (with Water): 16.38 dynes/cm @ 25.1 °C (77.2 °F)

Test Ranges

- **Superficial Gas Velocity:**

  5 to 26 m/s

- **Liquid Loading Level:**

  50 to 1200 m³/MMsm³

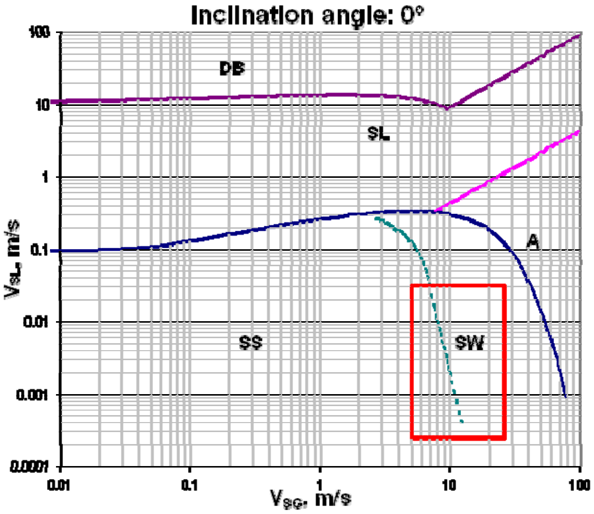
- **Water Cut:**

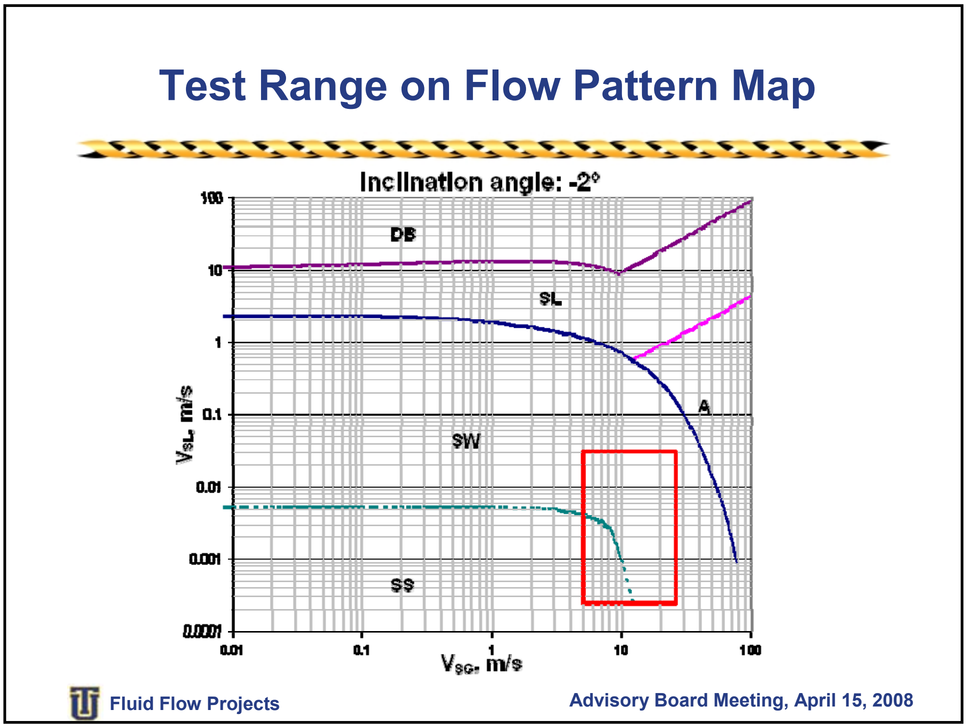
  0 to 1

- **Inclination Angles:**

  0º, +2º, -2º

Test Range on Flow Pattern Map

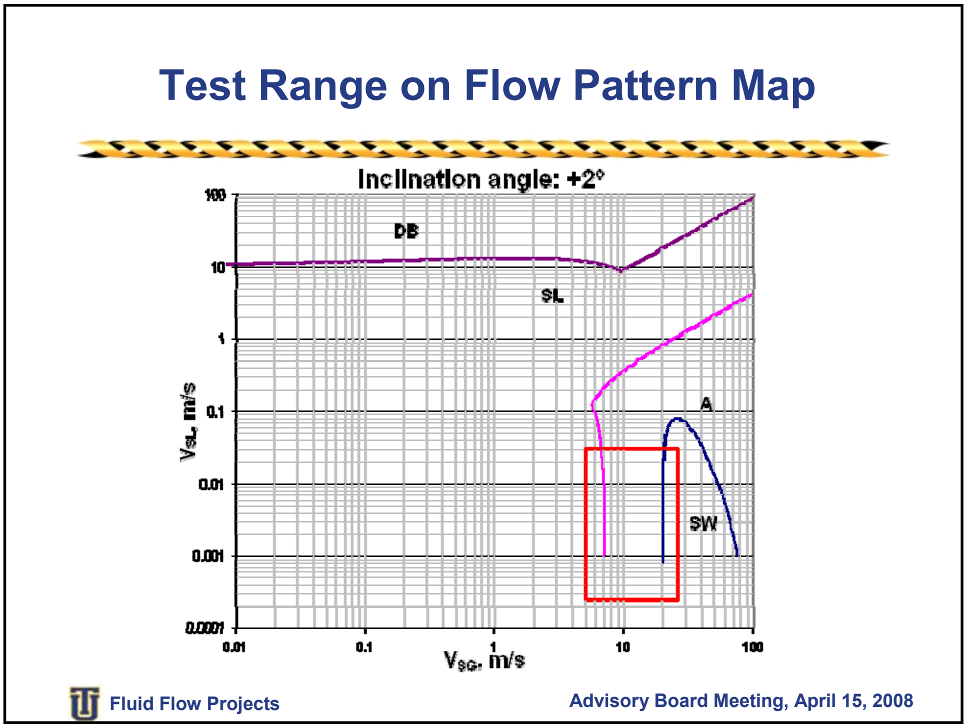




Test Range on Flow Pattern Map

Fluid Flow Projects

Advisory Board Meeting, April 15, 2008



Test Range on Flow Pattern Map

Fluid Flow Projects

Advisory Board Meeting, April 15, 2008

Model Evaluation

- Evaluate Unified Three-phase Model (Zhang and Sarica, 2006)
- Evaluate Existing Correlations
  - Droplet Entrainment Fraction
  - Gas-liquid Interfacial Friction Factor
  - Wetted Wall Fraction
- Modify Existing Correlations or Develop New Ones if Necessary

Project Schedule

- Horizontal Flow Tests — June 2008
- Inclined Flow Tests — September 2008
- Model Evaluation — November 2008
- Final Report — December 2008

Low Liquid Loading Gas-Oil-Water Flow in Near-Horizontal Pipes

Feng Xiao

PROJECTE COMPLETION DATES:

Horizontal Flow Tests	June 2008
Inclined Flow Tests	September 2008
Model Evaluation	November 2008
Final Report	December 2008

Objectives

The main objectives of this study are to investigate the hydrodynamics of low liquid loading gas-oil-water flow in near-horizontal pipes, to evaluate existing models and correlations, and to modify or develop new correlations if necessary.

Introduction

Low liquid loading gas-oil-water flow frequently occurs in wet gas transmission pipelines. These pipelines often contain water and hydrocarbon condensates. Small amounts of liquid can lead to significant increase of pressure loss along a pipeline and cause issues associated with hydrate formation, pigging frequency and downstream facility design. Therefore, it is necessary to better understand the flow characteristics of low liquid loading gas-oil-water flow. Due to the differences in fluid properties, co-current flow of oil and water with gas exhibits significantly different behaviors from that of single phase liquid with gas. While a few studies have been conducted on low liquid loading two-phase flow, there are very few studies on low liquid loading three-phase flow. Three-phase pipe flow has been investigated by several authors in terms of flow pattern and modeling, but none of them covers the range of low liquid loading pipe flow.

In a previous TUFFP experimental study of low liquid loading three-phase flow, 156 data points were acquired in horizontal pipe, and a preliminary data analysis conducted by Dong (2007). More experiments will be carried out for ±2^{o} inclined flow, and data analysis and model evaluation will follow.

Literature Review

Açikgöz et al. (1992) observed air-water-oil flows in a horizontal pipeline. The superficial velocities ranged from 0.15 to 50 m/s for gas and from 0.004 to 0.66 m/s for liquid. The oil superficial velocity was kept constant at 0.043, 0.09 and 0.24 m/s. Flow pattern maps were constructed with 10 flow patterns were identified.

Spedding et al. (2005) investigated oil-water-air flow for two different pipe ID's. A universal flow pattern map was developed by using dimensionless numbers for gas and liquid phases, respectively, as the mapping parameters. The dimensionless numbers were constructed in terms of pipe geometry, physical phase properties and flow rates of the phases.

Taitel et al. (1995) proposed a three-layer stratified flow model. Taitel (1976) transitions criterion from stratified flow to intermittent flow was applied and worked well at low gas flow rates.

Bonizzi et al. (2003) presented a model for three-phase slug and stratified flow. It is based on the two-fluid drift-flux model with a transport equation for one liquid phase. Closure relationships were incorporated to predict the liquid-liquid flow pattern, the phase inversion point, mixture viscosity and the slip between the liquid phases.

Zhang and Sarica (2006) proposed a unified model that governs all the flow patterns. The phase distributions and hydrodynamics are described based on two criteria: gas-liquid flow pattern and oil-water mixing status. Three-phase flow is treated as gas-liquid two-phase flow or three-layer stratified flow based on the oil/water mixing. Correlations were proposed for phase mixing and inversion.

Droplet entrainment and deposition is significant at high gas flow rates in stratified flow (Dong, 2007). Due to the lack of literature source on this for stratified flow, investigations for annular flow are presented below. Paras et al. (1991) proposed a model with two flux terms corresponding to turbulent diffusion and gravitational settling. This model predicts liquid concentration distribution and the circumferential variation of the deposition rate. Okawa et al. (2001) developed a correlation based on the assumption that the rate of droplet entrainment is characterized by the ratio of the interfacial shear force to the surface tension.

As for low liquid loading multiphase flow, Chen (1997) investigated air-oil flow in a horizontal 77.9-mm ID pipe, and proposed a mechanistic “double-circle” model with a correlation for interfacial friction factor. Meng (1999) investigated air-oil flow in horizontal and near horizontal 50.1-mm ID pipes, and proposed a model with a new correlation for interfacial friction factor and several evaluated corerelations for other parameters. Olive (2003) conducted air-water experiments in a near-horizontal 2-in ID pipe, and compared air-water data with air-oil data. Fan (2005) studied air-water horizontal and near horizontal flow in both 2-in ID and 6-in ID pipes. He proposed a mechanistic model with new correlations for wetted wall fraction, liquid-wall friction factor and interfacial friction factor. Dong (2007) conducted low liquid loading three-phase flow tests in a horizontal 6-in ID pipe. He conducted 156 tests, observed several new phenomena and classified 8 flow patterns within stratified flow. These investigations collectively recommended on more efforts for interface wave structure in upward flow, correlations for droplet entrainment fraction (Meng, 1999), liquid film distribution mechanism, flow close to the stratified-slug transition boundary (Fan, 2005), liquid phase mixing, and friction factors (Dong, 2007).

Experimental Study

Experimental Facility and Flow Loop

The experimental facility is shown in Fig. 1. A vertical three-phase separator is used for separating gas, oil and water phases. Inlet momentum is controlled by a bidirectional inlet diverter that also provides bulk gas/liquid separation. A 6-in thick wire mesh extractor is used to de-mist the air, which facilitates the removal of 99% of 5 micron and larger droplets. Oil and water separate in a liquid retention section at the bottom of the separator. A muffler was installed at the air outlet of the separator to reduce the noise resulting from high air flow rate. Two 500 gallon plastic tanks are used as oil and water tanks. Two progressive cavity pumps are used to circulate oil and water, respectively. Two-stage air compressor is used to supply air to the system.

The test section is made of 6-in ID pipes and consists of two runs connected with a U-shape bend. Each run is 56.4-m long steel pipe with a transparent acrylic section at the end of each, as shown in Fig. 2. The inclination angle of the test section can be changed from 0^o to $\pm 2^o$, making it possible to have downward flow and upward flow in the two runs, respectively, at the same time.

Instrumentation and Data Acquisition

The instrumentation was selected according to the measurements of the desired parameters: pressure gradient, holdups of the three phases, liquid film thicknesses, liquid wetted wall fractions and liquid entrainments in the gas phase.

Gas flow rate is measured with a Micro Motion flow meter CMF300. Two Micro Motion flow meters CMF050 are used to measure oil and water flow rates.

Quick-closing valves are used to trap the liquid to measure the total liquid, water and oil holdups. The liquid trapped between the quick-closing valves is pigged out with a pigging system and drained into graduated cylinders to be measured.

A cold liquid injection method is applied to measure the interface velocity. A cold liquid injector is placed at a point in the test section to inject cold oil or water into the test section. Two thermocouples are installed 0.5 ft after the injector with a 1-ft long interval between them. The time difference between the temperature peaks detected by the two thermocouples is recorded, and used to calculate the liquid velocity.

A Conductivity probe is employed to measure the water film thickness at the bottom of the pipe. During the experiments, the conductivity probe traversed vertically to detect the interface position between oil and water. The conductivity probe is also used to determine which phase is continuous.

An iso-kinetic sampling system is used to determine liquid entrainment in the gas phase. The probe captures the sample at different locations. The liquid obtained is separated by a small gas-liquid separator and measured in a graduated cylinder. The liquid volumes and the sampling times are used to determine the liquid entrainment. Liquid entrainment at each location is obtained as the probe traverses from bottom to top, giving a liquid entrainment profile across the pipe. The principle is shown in Fig. 3.

A cross-sectional viewing system is mounted in the test section to give an image of the cross section. An Olympus rigid borescope, an Olympus SP350 digital camera and a camera-borescope adapter are used in this system. Sheet light illumination is used to illuminate the pipe cross-section. The method is to enclose the pipe with dark covers, leaving a narrow gap to restrict the light to a narrow area. The principle of the axial viewing system is shown in Fig. 4.

Marked scales on the inner wall of the transparent acrylic section give direct readings of the wetted wall perimeter of both oil and water phases.

A DeltaV^{TM} digital automation system is used as the data acquisition system. The DeltaV system is a fully digital system, which saves time and also can minimize errors when processing the measured parameters.

Test Fluids

The fluids that will be used in the experiments are air, mineral oil and tap water. Due to its good separability and stability, Tulco Tech 80 oil was selected as the oil phase. The physical properties of the oil are given below (Dong, 2007).

- API gravity: 33.2°
- Density: 858.75 kg/m^3 @ 15.6 ^{o}C
- Viscosity: 13.5 cp @ 40 ^{o}C
- Surface tension: 29.14 dynes/cm @ 25.1 ^{o}C
- Interfacial tension against water: 16.38 dynes/cm @ 25.1 ^{o}C
- Pour point temperature: -12.2 ^{o}C
- Flash point temperature: 185 ^{o}C

Test Range

In this study, gas velocities will range from 5 m/s to 26 m/s. The liquid loading level will range from 50 to 1200 m^3/MMsm^3. The water cut will be varied from 0 to 100%. Accordingly, superficial total liquid velocity will range from 0.00025 m/s to 0.0312 m/s. Inclination angles are -2^o and +2^o from horizontal. Horizontal flow tests will also be conducted to investigate droplet entrainment and deposition at superficial gas velocities higher than 17.5 m/s. Fig. 5 shows the gas-liquid test matrices on the flow pattern maps.

Model Evaluation

According to flow pattern maps and previous studies of low liquid loading two-phase flow, it is possible to encounter stratified flow, slug flow and annular flow in the investigation of low liquid loading flow in slightly inclined pipes. The Zhang and Sarica (2006) Unified Three-phase model for the model evaluation. The first part will involve evaluating the whole performance of the Unified Three-phase model. The second part will evaluate existing correlations, particularly for droplet entrainment, gas-liquid friction factor and wetted wall fraction. If necessary, existing correlations will be modified or new correlations will be developed based on the experimental data.

Project Schedule

- Horizontal flow tests – June 2008
- Inclined flow tests – September 2008
- Model evaluation – November 2008
- Final report – December 2008

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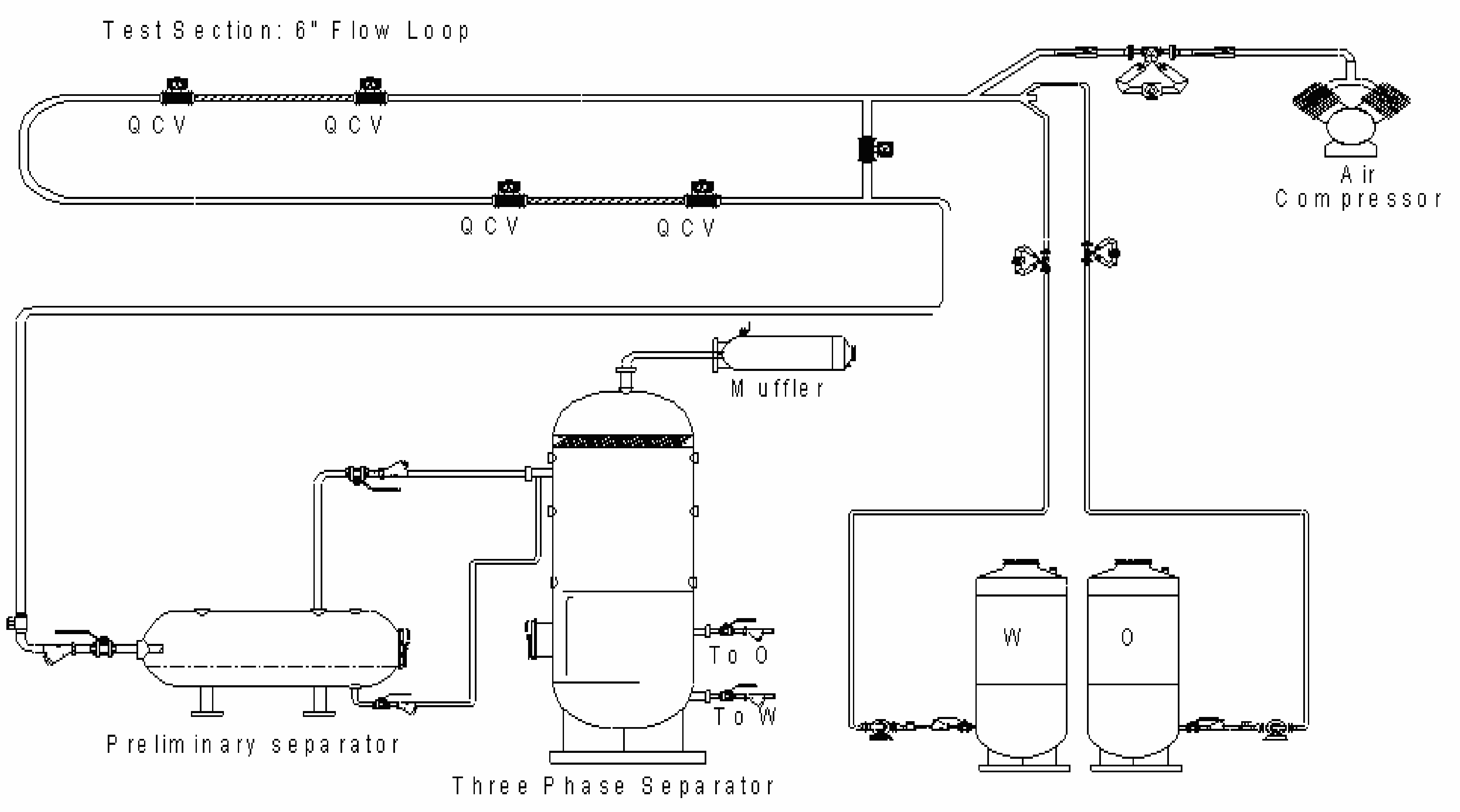


Fig. 1: Experimental Facility

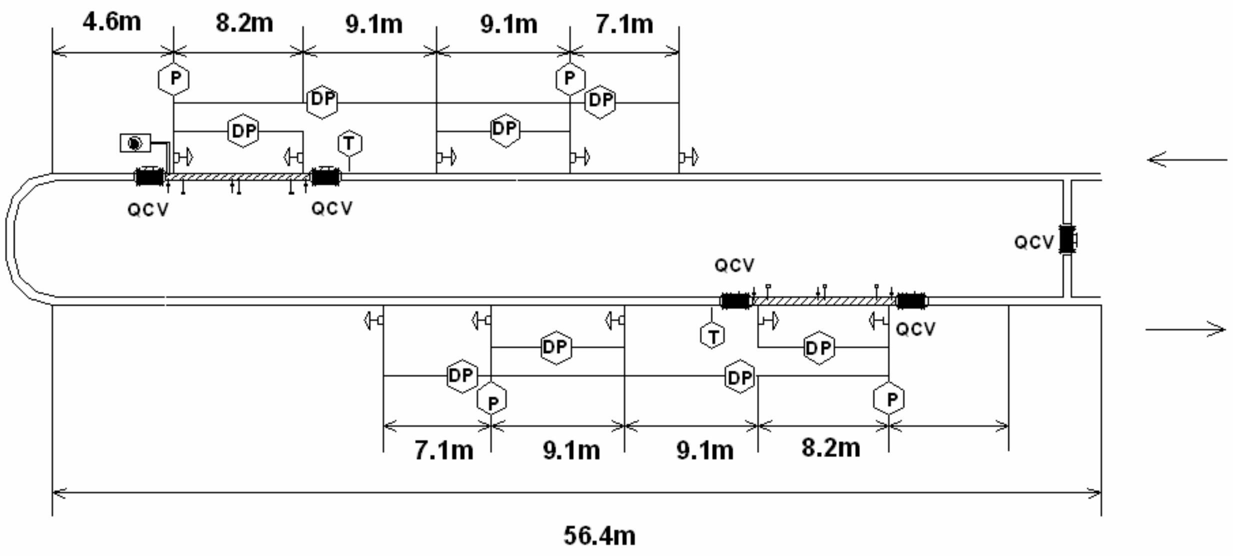


Fig. 2: Test Section

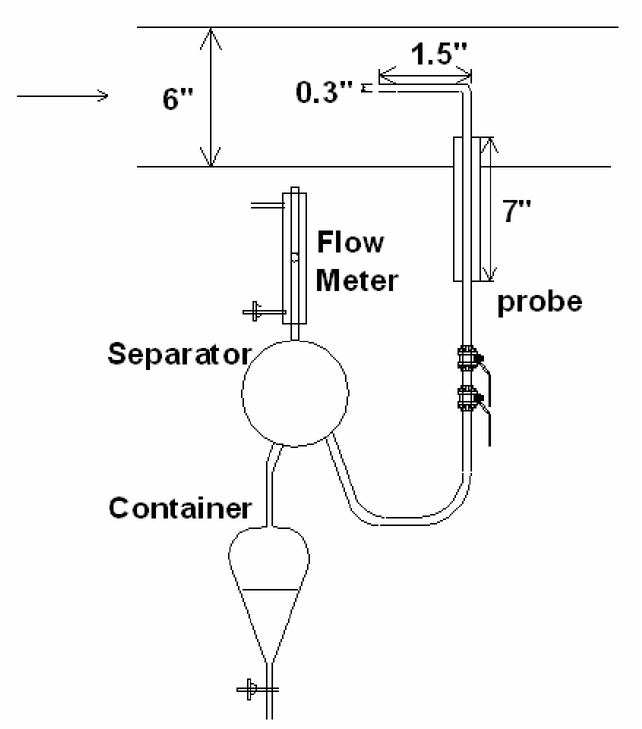


Fig. 3: Iso-kinetic Probe

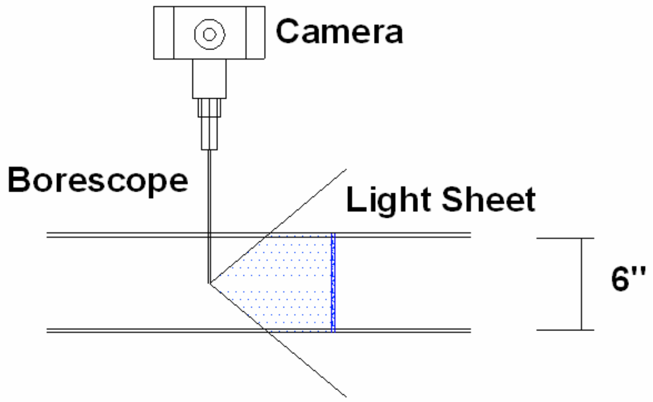


Fig. 4: Cross-sectional Viewing System

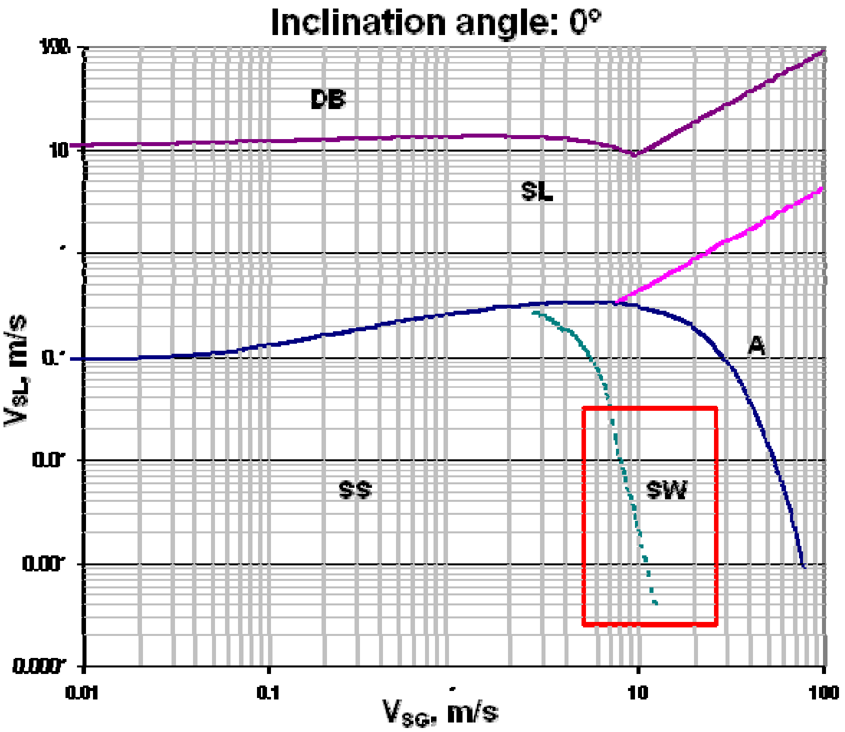


Fig. 5-a: Test Matrix on Flow Pattern Map, θ=0° From Horizontal

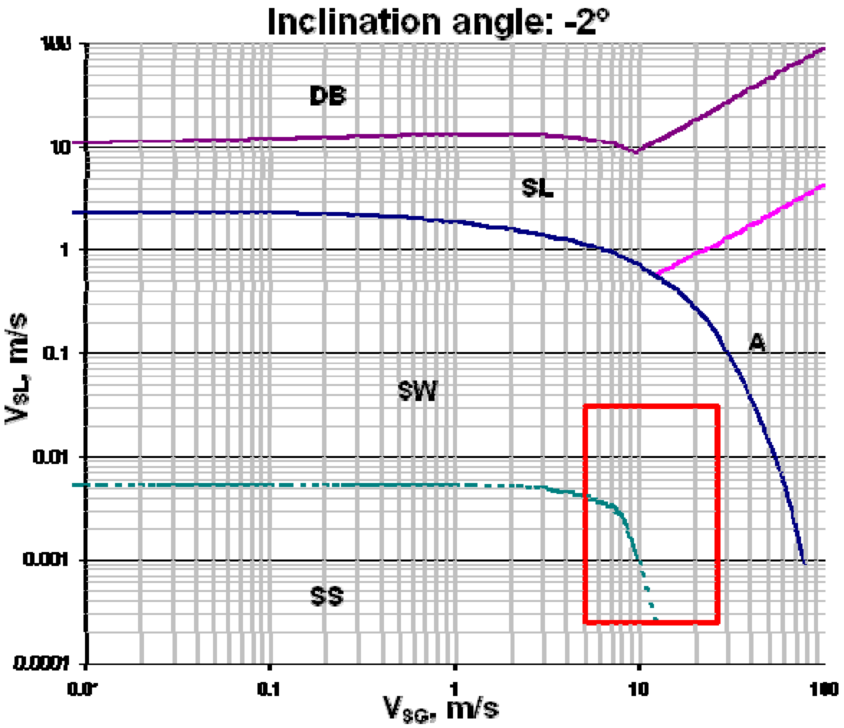


Fig. 5-b: Test Matrix on Flow Pattern Map, θ=-2° From Horizontal

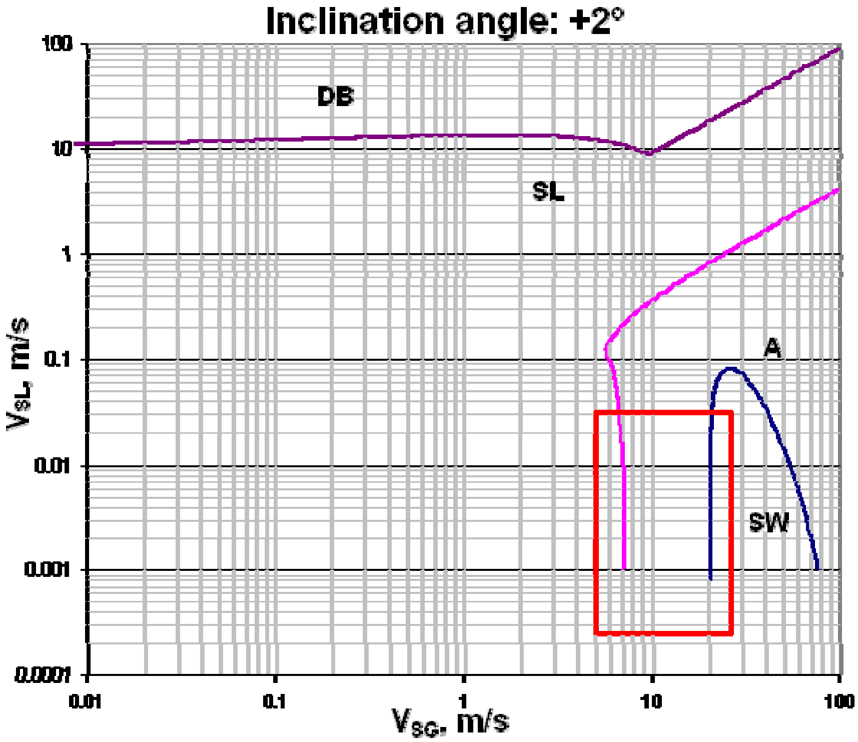


Fig. 5-c: Test Matrix on Flow Pattern Map, θ=+2° From Horizontal

Unified Model

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

Unified Model …

- Current Activities
  - Incorporation of Various TUFFP Studies Feed Unified Model in Closure Relationships
  - Code and Software Improvement Efforts
  - Three-phase Performance Testing
    - Utilization of Existing Three-phase Data

Unified Model …

- Current Activities …
  - Code Improvement Activities
    - Cooperation with Schlumberger
    - Robustness and Accuracy Significantly Improved
  - Software Improvement
    - New GUI

Unified Model …

- Future Activities
  - Continue Improvements in Both Modeling and Software Development

Fluid Flow Projects

Unified Model and Computer Program Updates

Holden Zhang

Advisory Board Meeting, April 15th, 2008

Outline

- Objectives
- Unified Model Testing
- 3-P Unified Model Compared with Data Bank
- TUFFPT – Demo

Objectives

- Develop Robust Computer Programs Based on TUFFP Unified Models
    - Unified Format – Inputs, Outputs, …
    - Easy Plug in Commercial Simulators
    - Easy Use by Other Models – Heat Transfer, Wax Deposition, Three-Phase Flow
- Develop Useful Tools for Members
    - TUFFPT – Tulsa University Fluid Flow Prediction Tools

Unified Model Testing

- Two-Phase Unified Model Incorporated into Schlumberger's PIPESIM
- Improved Program Convergence
- Harness Testing for
    - Two-Phase
    - Three-Phase

2-P Unified Model Harness Tests

- Ranges
  - V_{SL}: 0.001 – 100 ft/s
  - V_{SG}: 0.001 – 300 ft/s
  - θ: -90 – 90 degree
  - d: 0.5 – 50 inch
  - ρ_L: 40 – 80 lbm/ft^3
  - μ_L: 0.001 – 10,000 cp
  - μ_G: 0.005 – 0.04 cp
  - σ: 1.0 – 100 dynes/cm
  - P: 10.0 – 15,000 psia
  - ε/d: 0.0 – 0.5

2-P Unified Model Harness Tests …

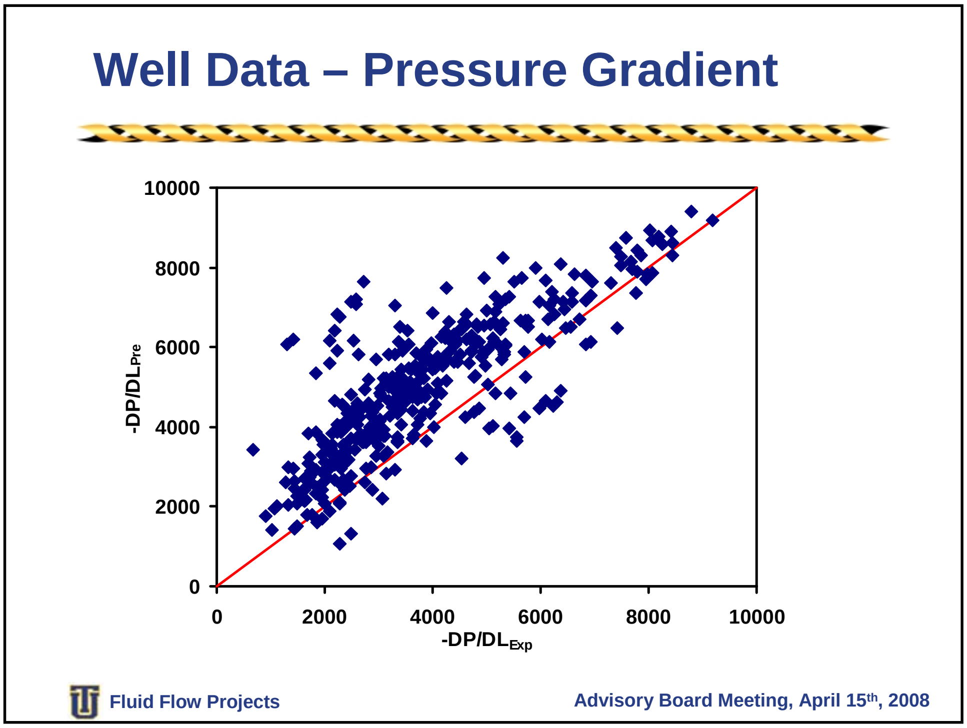
- 10,000 Cases Run
- Randomly Selected Flow Parameters
- Performances
  - Finished in 7 sec on a PC
  - Convergence improved from 90% to 99%

3-P Unified Model Testing

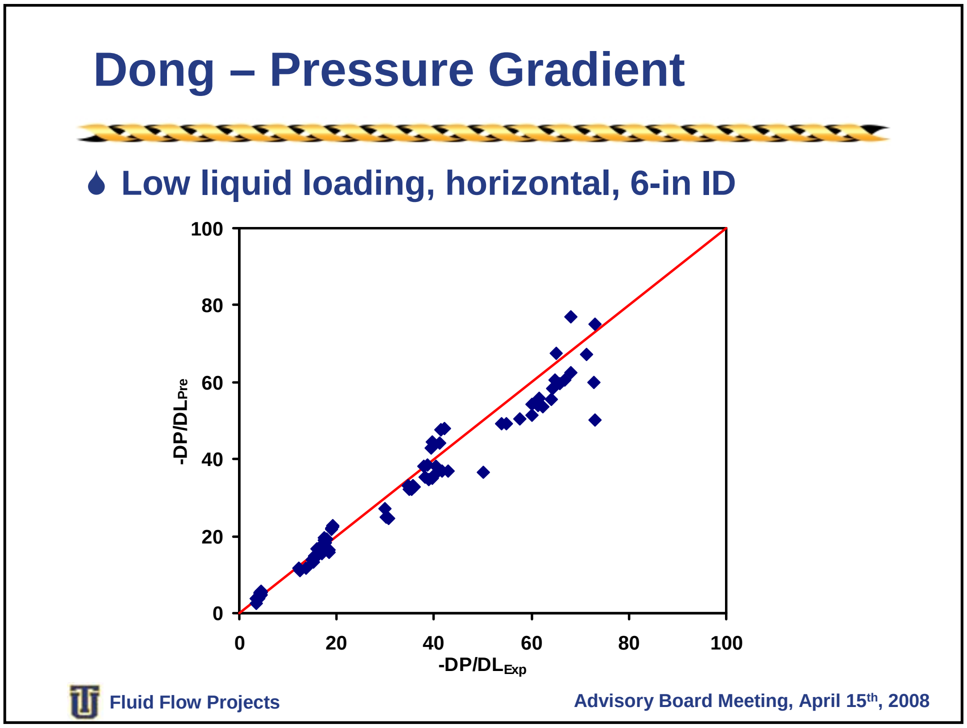
- Similar Harness Tests Carried out for 3-P Unified Model
- Similar Convergence Rate (>99%)

3-Phase Data Bank

- Comparisons with 3-Phase Data after Improvements in Convergence
  - Well Data (from TUFFP Well Databank – 392
  - TUFFP Dong Low Liquid Loading Data (2007) – 88
  - TUFFP Keskin Data (2005) – 213
  - Hall (1992) – 93
  - TUFFP Laflin and Oglesby (1976) – 79
  - Malinowski (1975) – 34
  - Sobocinski (1955) – 114



Well Data – Pressure Gradient

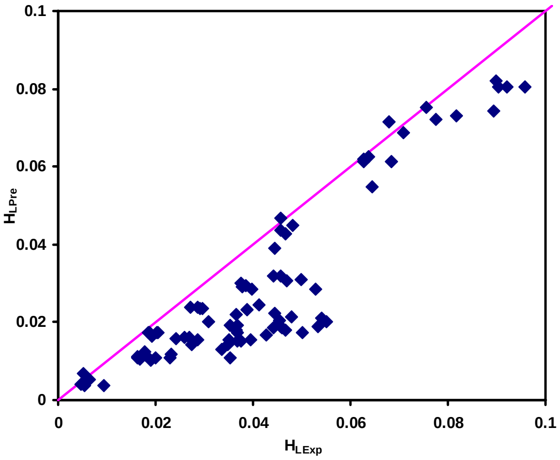


Dong – Pressure Gradient

- Low liquid loading, horizontal, 6-in ID

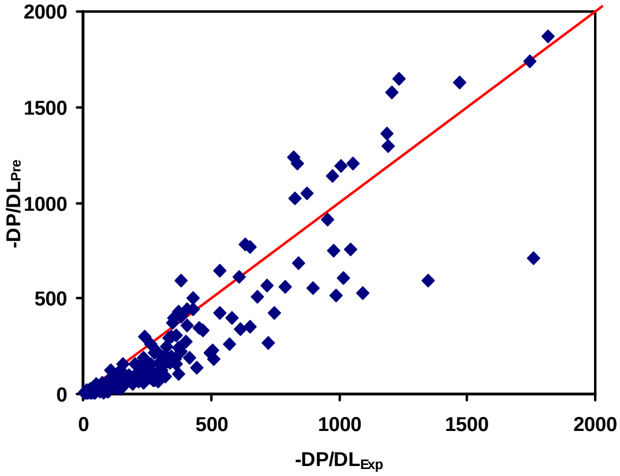
Dong – Liquid Holdup

- Low liquid loading, horizontal, 6-in ID



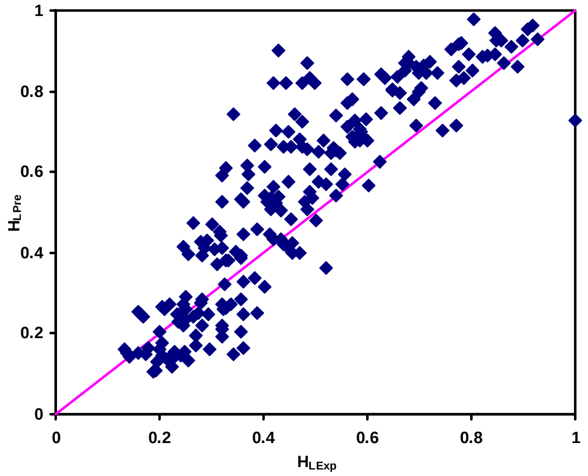
Keskin – Pressure Gradient

- Horizontal, 2-in ID



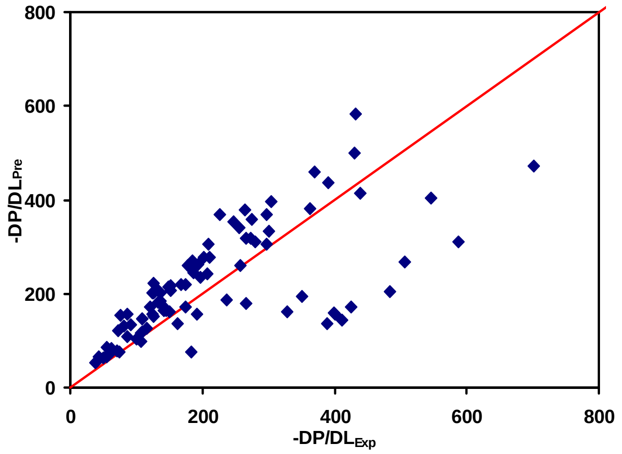
Keskin – Liquid Holdup

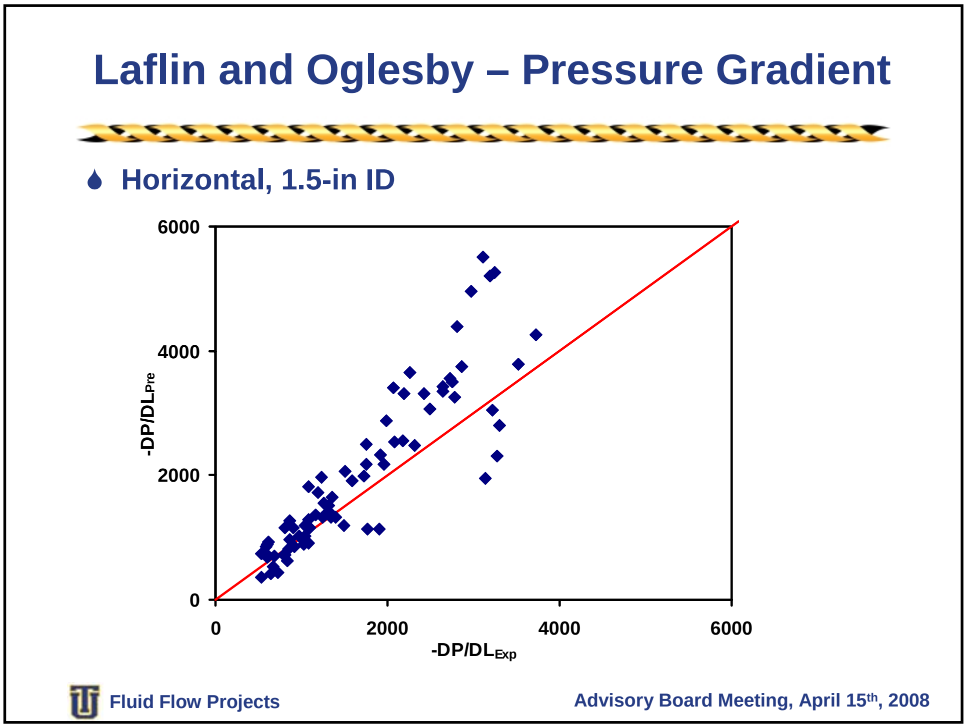
- Horizontal, 2-in ID



Hall – Pressure Gradient

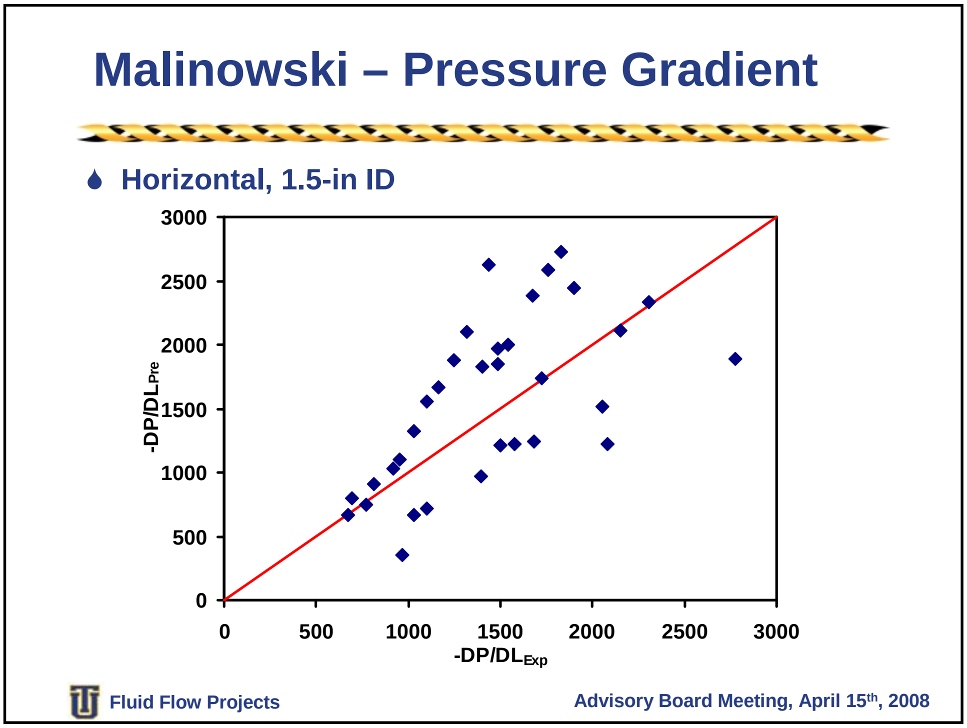
- Horizontal, 3-in ID





Laflin and Oglesby – Pressure Gradient

- Horizontal, 1.5-in ID

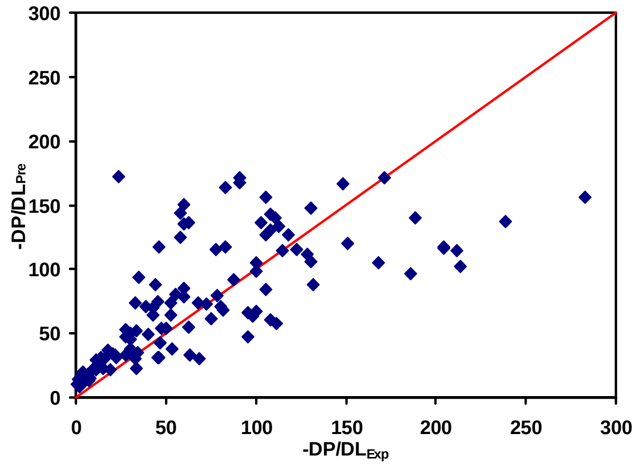


Malinowski – Pressure Gradient

- Horizontal, 1.5-in ID

Sobocinski – Pressure Gradient

- Horizontal, 3-in ID



Documentations

- Living Document – Modeling Methods
  - All Basic Equations and Closure Relationships in Current Model
  - Two-phase Model as Part of Three-phase Model

Documentations …

- Modification History
  - Document All Improvements in Models and Computer Programs

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TUFFPT – Demo

- Four Features
  - Flow Pattern
  - Case Study
  - Contour Plot
  - Well and Pipeline

Fluid Flow Projects

Generalized Model for Dead and Live Heavy Oils

Holden Zhang

Advisory Board Meeting, April 15th, 2008

Outline

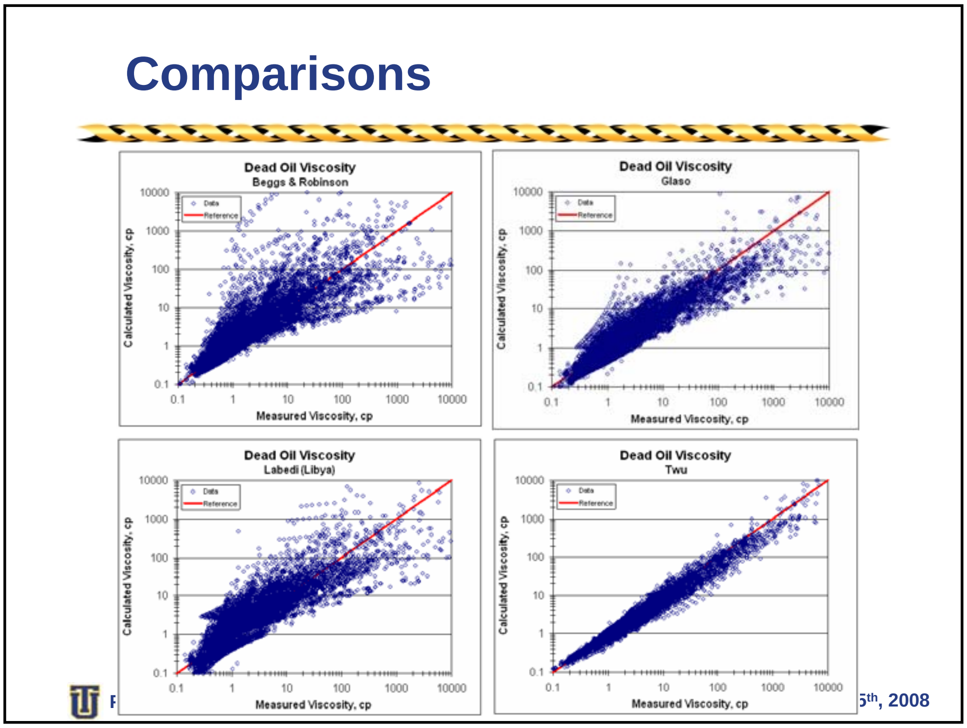
- Introduction
- Dead Oil Viscosity
  - Modeling
  - Comparison with Data
- Live Oil Viscosity
  - Modeling
  - Comparison with Data

Introduction

- Heavy Oil Viscosity Modeling
    - Difficult to Predict
    - Crucial for Heavy Oil Multiphase Flow Modeling
    - Preliminary Model Developed before JIP Formation
    - Revisiting Activated by Bergman and Sutton Presentation at 2007 SPE ATCE (SPE 110194)

Introduction …

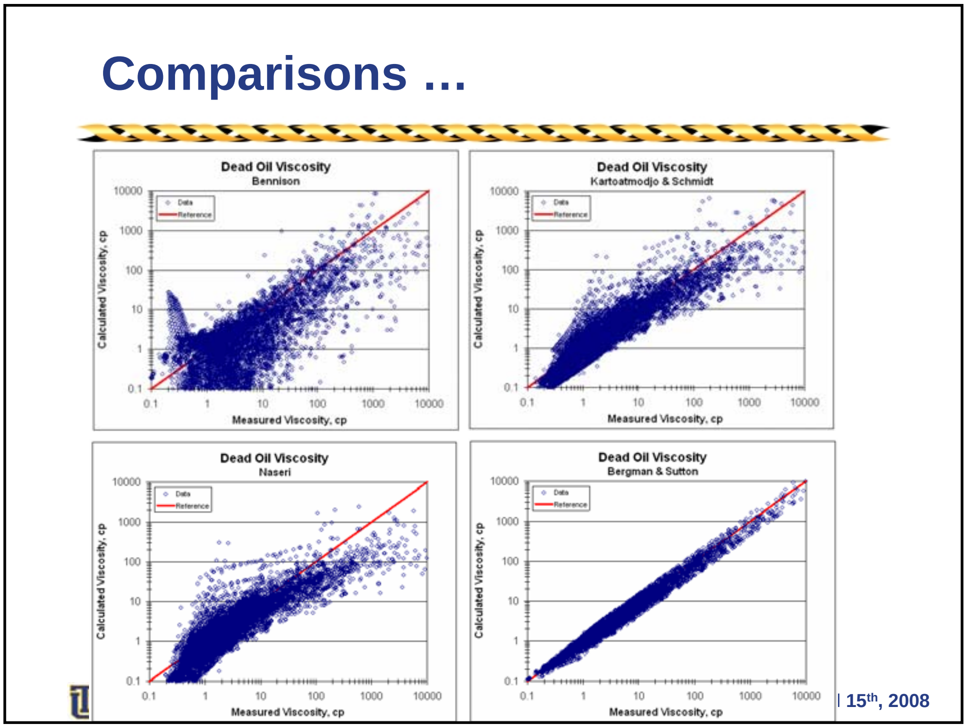
- Dead Oil Viscosity Correlations
    - Most as Function of Oil Gravity and Temperature $\mu_{od} = f(\gamma_{API}, T)$
    - Few also Considered Boiling Temperature $\mu_{od} = f(\gamma_{API}, T_b, T)$
    - Bergman and Sutton Compared 24 Models with 9800 Data



Comparisons

F

5th, 2008



Comparisons …

| 15th, 2008

Parameter Considerations

- Twu: $\mu_{od} = f\left(\gamma_{API}, T_b, T\right)$

- Bergman and Sutton Used Watson Characterization Factor:

$$\mu_{od} = f\left(\gamma_{API}, K_w, T\right)$$

$$K_w = \frac{T_b^{1/3}}{\gamma_o}$$

Parameter Considerations …

- Riazi and Daubert (1980): Boiling Temperature Related to Molecular Weight and Specific Gravity
- Whitson (2000):

$$K_w = 4.5579 M_o^{0.15178} \gamma_o^{-0.84573}$$

Model – Dead Oil Viscosity

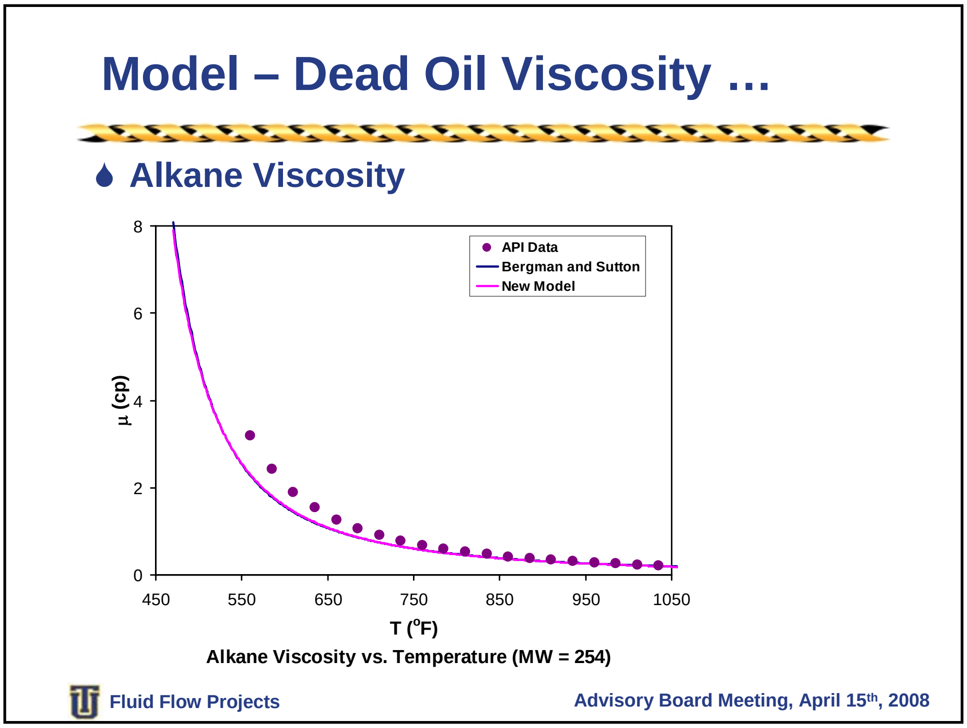
- Relating Oil Viscosity to Oil Density, Molecular Weight and Temperature:

$$\mu_o = f\left(\rho_o, M_o, T\right)$$

  - Easy to use in PVT software
  - Unified dead and live oil viscosity predictions

Model – Dead Oil Viscosity …

- Correlation Developed to Reproduce Bergman and Sutton (2007) Predictions
  - First for Alkane Viscosity
  - Then for Oil Based on Density Deviation from Alkane Corresponding to Same Molecular Weight
  - Finally Fit to CVX Data for Temperature Trend and Compare with Marathon Data Base



Model – Dead Oil Viscosity …

- Alkane Viscosity

Alkane Viscosity vs. Temperature (MW = 254)

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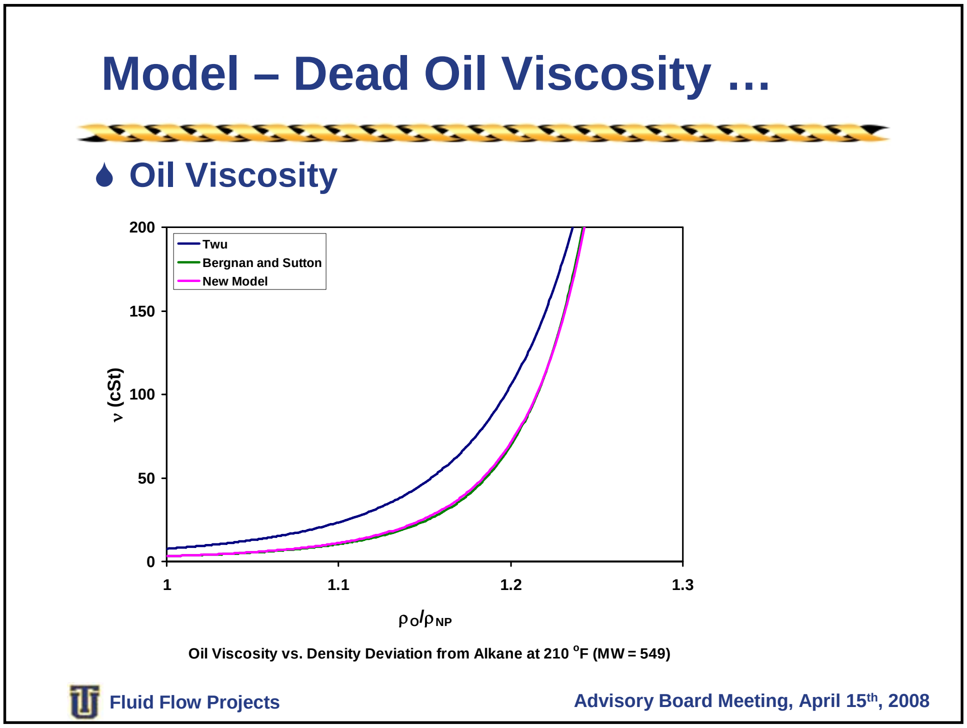

Model – Dead Oil Viscosity …

- Oil Viscosity

Oil Viscosity vs. Density Deviation from Alkane at 210 °F (MW = 549)

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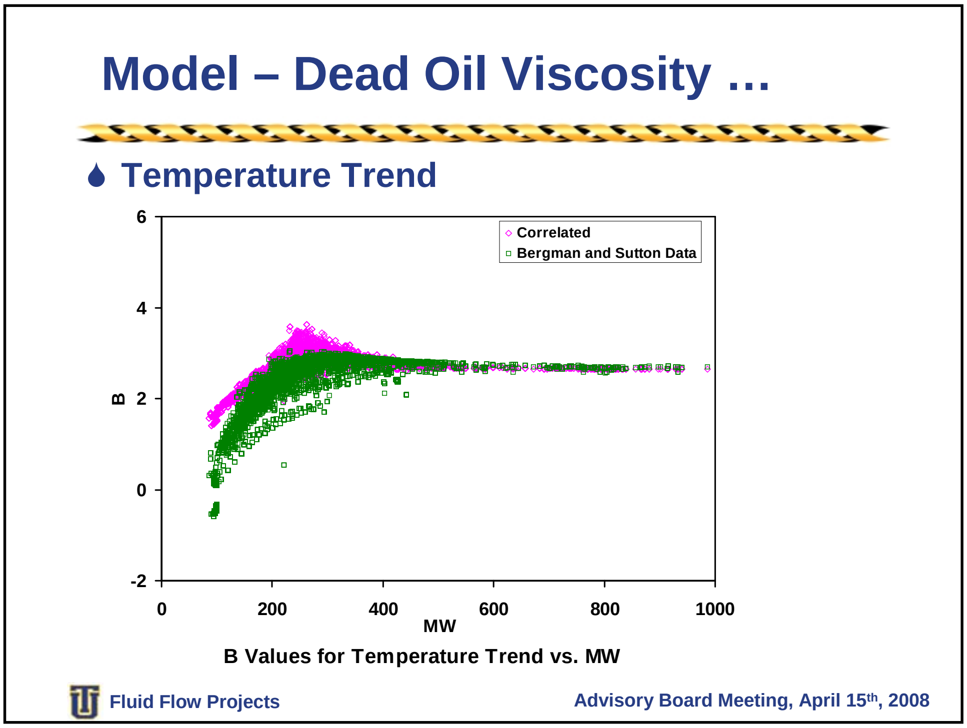

Model – Dead Oil Viscosity …

- Temperature Trend

B Values for Temperature Trend vs. MW

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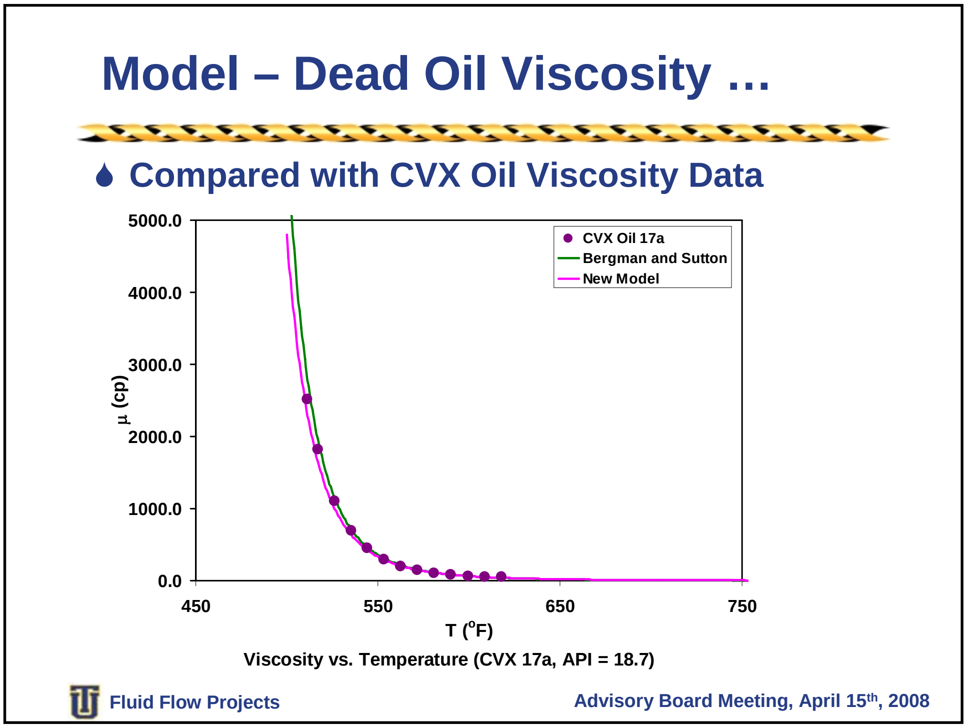

Model – Dead Oil Viscosity …

- Compared with CVX Oil Viscosity Data

Viscosity vs. Temperature (CVX 17a, API = 18.7)

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Model – Dead Oil Viscosity …

- Temperature Trend Based on Bergman Method

$$\mu = \left(\rho_{210}\nu_{210} + 1\right)^{\left(\frac{520}{T-150}\right)^{B}} - 1$$

- Correlation for B

$$B = 2.65\left(1 - \frac{1}{EXP\left(0.01MW\right)}\right)\left(\frac{\rho_o}{\rho_{NP}}\right)_{60}^{\frac{2.4}{EXP\left(0.01\left|MW-250\right|\right)}}$$

Model – Dead Oil Viscosity …

- Viscosity at 210 ºF

$$\nu_{210} = \nu_{210NP} EXP\left[\frac{1000}{MW}\left(R_D^{13.8\left(0.0002\left(MW+70\right)\right)^{\left(250/MW\right)}+0.12} - 1\right)\right]$$

$$\nu_{210NP} = 6.5\left(0.000022 * \left(MW + 1000\right)\right)^{\left(130/MW\right)} + 0.28$$

$$R_D = \left(\frac{\rho_{o210}}{\rho_{NP210}}\right)$$

Model – Dead Oil Viscosity …

- Densities

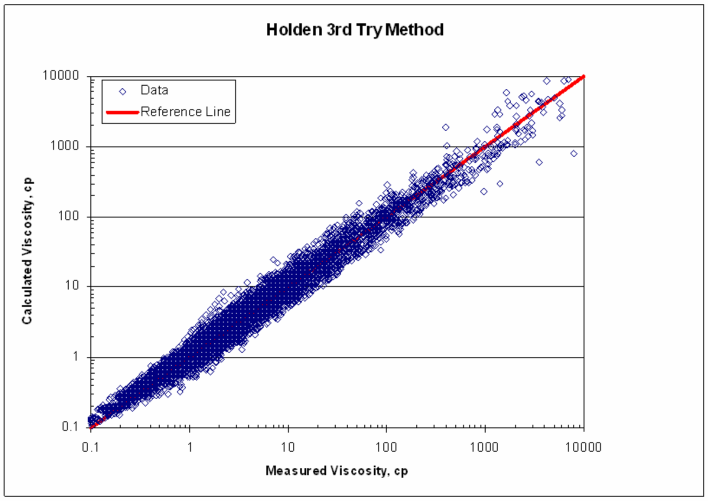
$$\rho_{NP210} = 0.80248 - \frac{10.1}{MW^{0.87}}$$

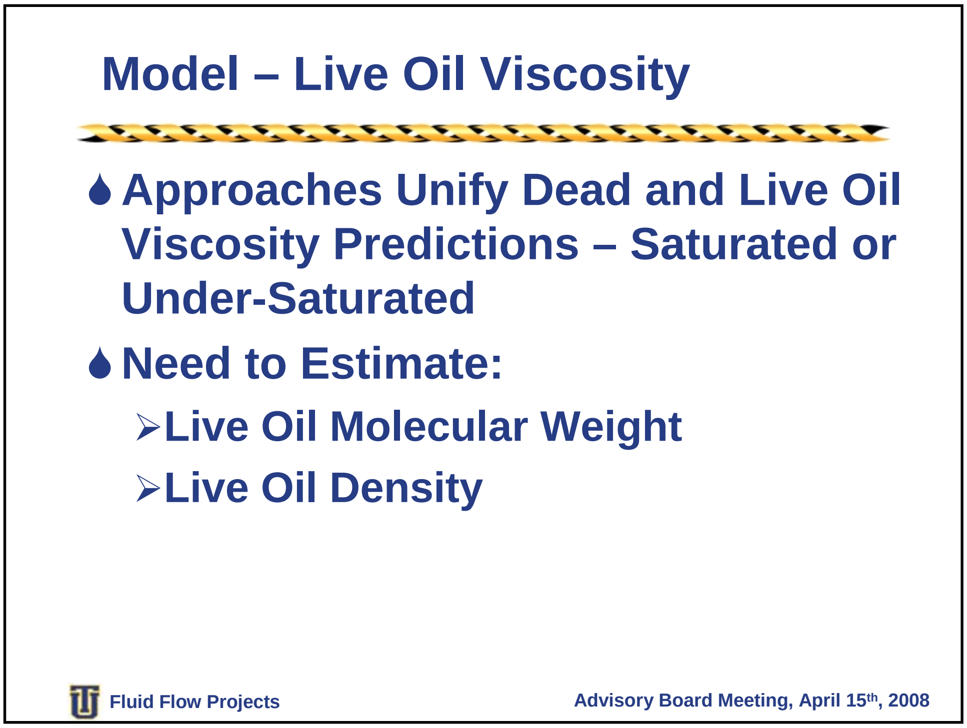
$$\rho_{o210} = \rho_{o60} EXP\left(-150\alpha\left(1 + 0.8 \times 150\alpha\right)\right)$$

$$\alpha = \frac{0.00025042 + 0.00008302\rho_{o60}}{\rho_{o60}^{2}}$$

Model – Comparisons

- Comparable to Bergman and Sutton Accuracies





Model – Live Oil Viscosity

- Approaches Unify Dead and Live Oil Viscosity Predictions – Saturated or Under-Saturated
- Need to Estimate:
  - Live Oil Molecular Weight
  - Live Oil Density

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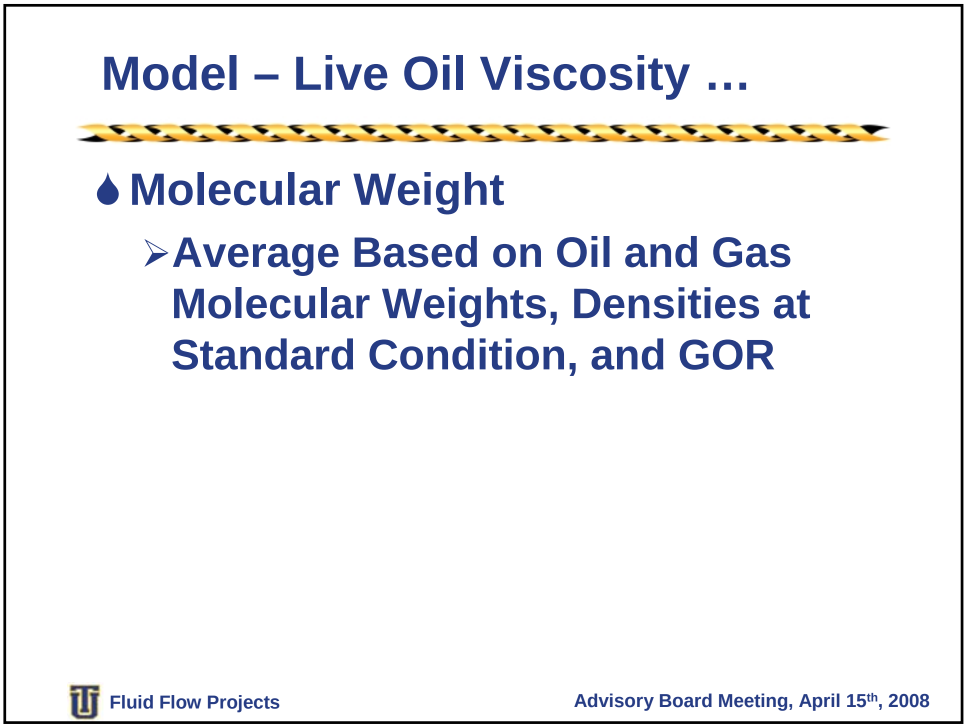

Model – Live Oil Viscosity …

- Molecular Weight
  - Average Based on Oil and Gas Molecular Weights, Densities at Standard Condition, and GOR

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Model – Live Oil Viscosity …

- Saturated Oil Density (Standing, 1981)

$$\rho_o = \frac{62.4\gamma_o + 0.0136 R_S \gamma_g}{0.972 + 0.000147\left[R_S\left(\frac{\gamma_g}{\gamma_o}\right)^{0.5} + 1.25(T-460)\right]^{1.175}}$$

  - Gas Solution Ratio

$$R_S = \gamma_g\left[\left(\frac{P}{18.2} + 1.4\right)10^{0.0125 API - 0.00091(T-460)}\right]^{1.2048}$$

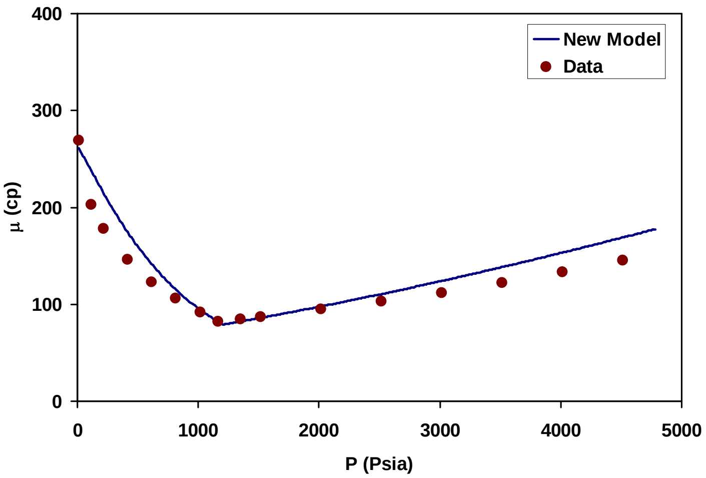
Model – Live Oil Viscosity …

- Under-Saturated Oil Density (Ahmed, 1985)

$$\rho_o = \rho_{ob} EXP\left[D\left(EXP(-0.0001847272P) - EXP(-0.0001847272P_b)\right)\right]$$

$$D = \frac{1.026638 + 0.0001553\left[R_S\left(\frac{\gamma_g}{\gamma_o}\right)^{0.5} + 1.25(T-460)\right]^{1.175}}{-11.526938 - 0.00251229 R_S \gamma_g}$$

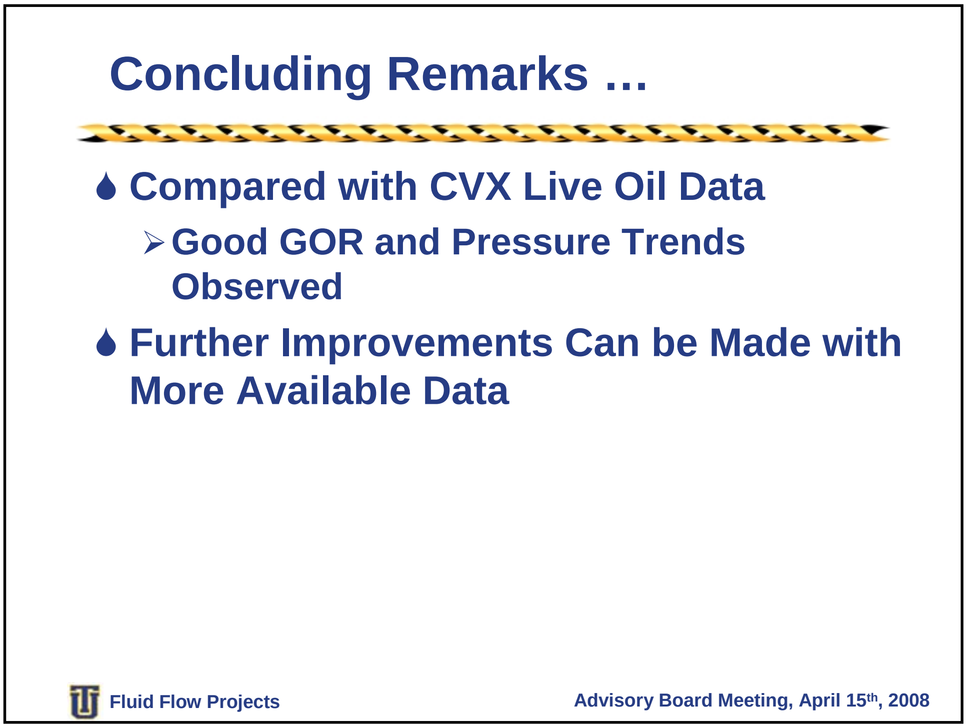
Model – Live Oil Viscosity



Live Oil Viscosity vs. Pressure (CVX Oil 2, API = 18.9)

Concluding Remarks

- Model Correlates Oil Viscosity as Function of Molecular Weight, Oil Density and Temperature
  - Unifies Dead and Live Oil Viscosity Predictions
- Compared with Marathon 9800 Data
  - Accuracies Comparable to Bergman and Sutton Model



Concluding Remarks …

- Compared with CVX Live Oil Data
  - Good GOR and Pressure Trends Observed
- Further Improvements Can be Made with More Available Data

Three-phase Hilly Terrain Flow

- Significance
  - Valleys and Hills may Act as Local Separation Devices for Fluids
  - Location, Amount and Residence Time of Water in a Pipe can have Significant Impact on Flow Assurance Issues such as Hydrate Formation and Corrosion

---

Three-phase Hilly Terrain Flow …

- Past Studies
  - Hilly Terrain Flow of Two Phases has been Studied Extensively
    - Al-Safran, 1999 and 2003
    - Others Outside of TUFFP
  - No Available Research is Found on Three-phase Flow

Three-phase Hilly Terrain Flow …

- Current Project
  - Objectives
    - Observe Flow Behavior and Identify Flow Characteristics, Focusing on Water Phase
    - Develop Predictive Tools (Closure Relationships or Models) to Quantify the Impact of Water Phase

Three-phase Hilly Terrain Flow …

- Status
  - Gizem Ersoy, Ph.D. Student, Looked at Feasibility of Using 1400-ft. Long Loop
  - Decided that Three-phase Gas-Oil-Water Facility is More Suitable
  - Facility Modification Design is Complete
  - Implementations of Modifications are Underway

Fluid Flow Projects

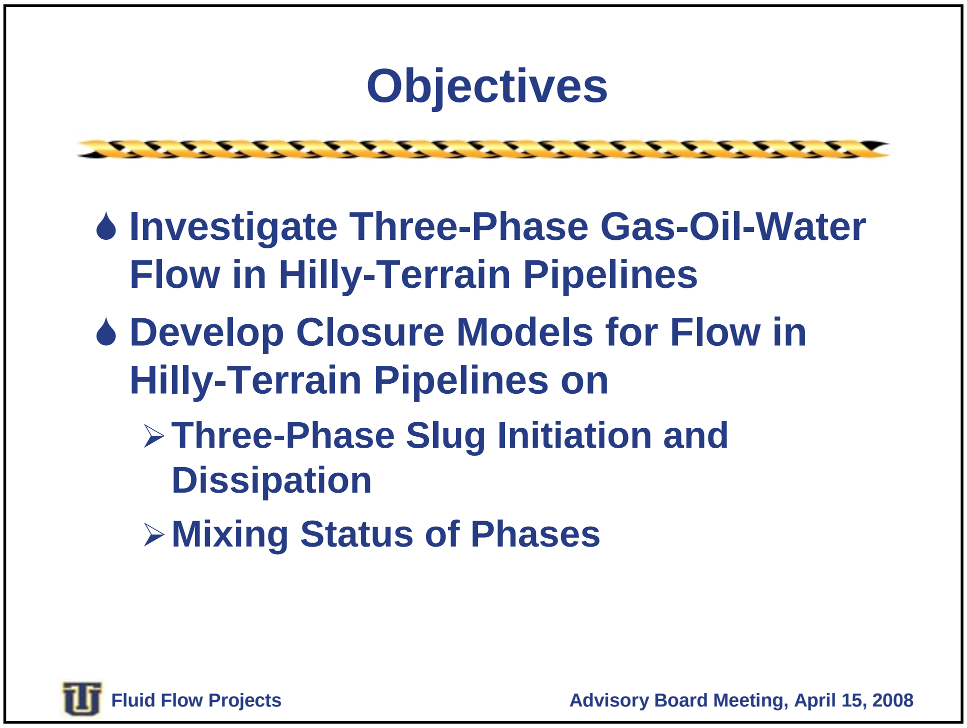
Investigation of Three-Phase Gas-Oil-Water Flow in Hilly-Terrain Pipelines

Gizem Ersoy Gokcal

Advisory Board Meeting, April 15, 2008

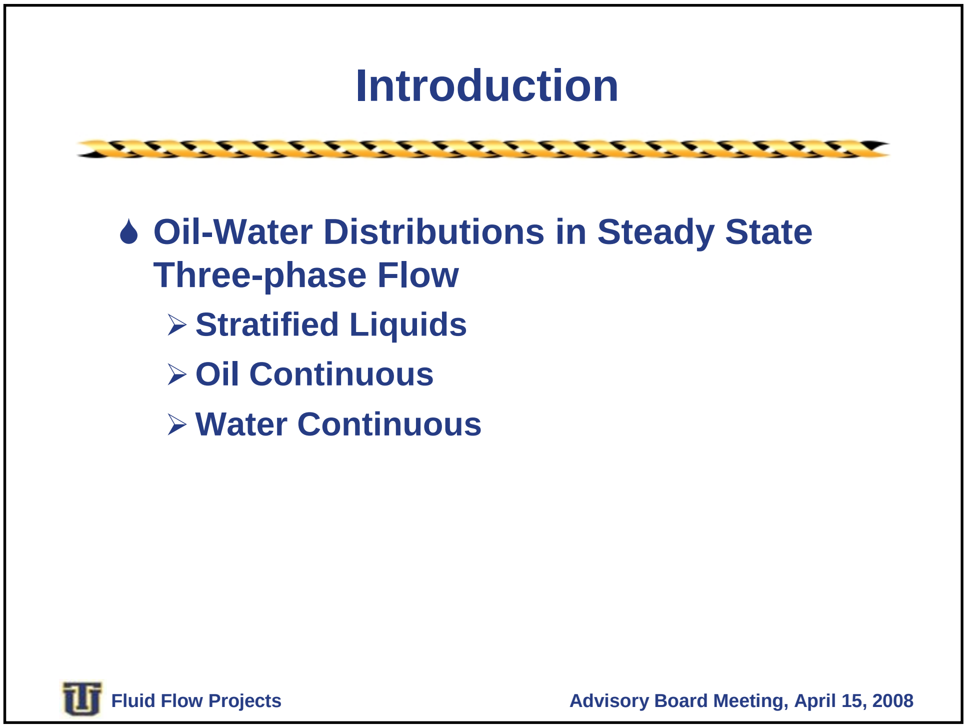
Outline

- Objectives
- Introduction
- Significance
- Three-Phase Flow Effects
- Experimental Study
- Preliminary Modeling
- Project Schedule



Objectives

- Investigate Three-Phase Gas-Oil-Water Flow in Hilly-Terrain Pipelines
- Develop Closure Models for Flow in Hilly-Terrain Pipelines on
  - Three-Phase Slug Initiation and Dissipation
  - Mixing Status of Phases

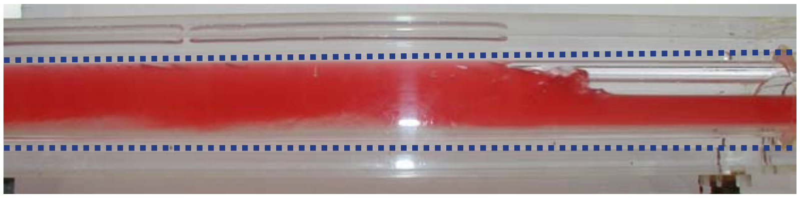


Introduction

- Oil-Water Distributions in Steady State Three-phase Flow
  - Stratified Liquids
  - Oil Continuous
  - Water Continuous

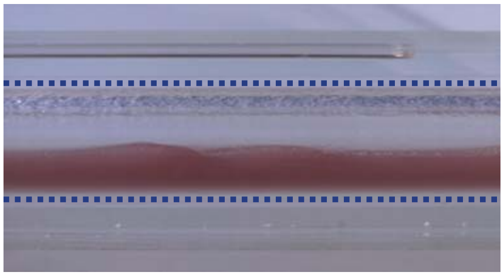
Introduction ...

- Stratified Liquids



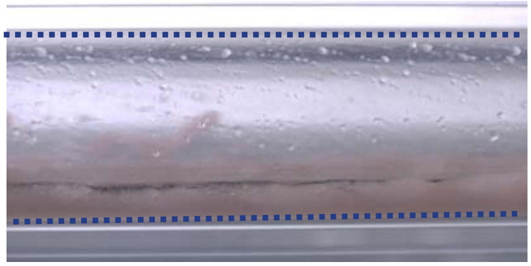
Introduction ...

- Oil Continuous



Introduction ...

- Water Continuous



Introduction ...

- Hilly-Terrain Pipelines Consist of Horizontal, Upward and Downward Inclined Sections

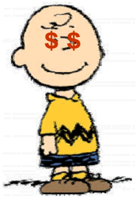
Introduction ...

- Flow May Exhibit Different Behavior

Significance

Hilly-Terrain Pipelines Cause

- Operational Problems
  - Flooding of Downstream Facilities
  - Severe Pipe Corrosion
  - Structural Instability of Pipelines
- Poor Reservoir Management
- Production Loss

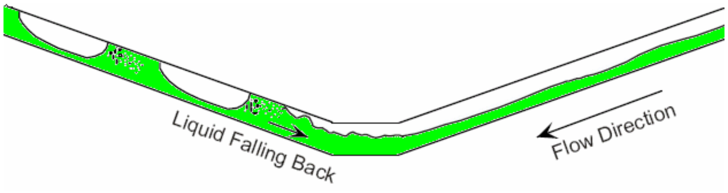


Significance ...

- Change in Slug Characteristics
  - Slug Length
  - Slug Frequency
  - Slug Translational Velocity
  - Liquid Holdup
- Water Effects
  - Flow Assurance Problems
    - Hydrates
    - Emulsions
    - Paraffin Deposition
    - Corrosion

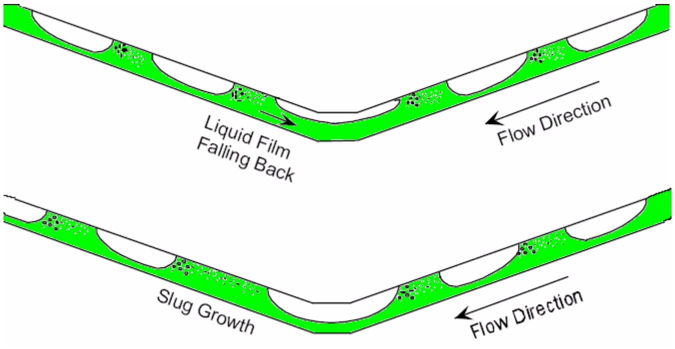
Three-Phase Flow Effects

- Hydrodynamics
  - Case-1



Three-Phase Flow Effects ...

- **Hydrodynamics**
  - Case-2



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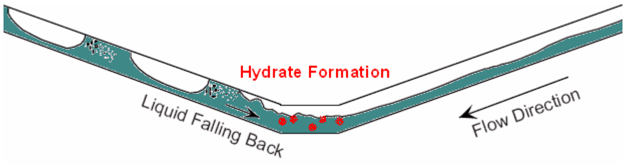
Three-Phase Flow Effects ...

- **Flow Assurance:**
  - Hydrates
    - Segregated Water Can Accelerate Hydrate Formation
    - Oil-Water Dispersions/Emulsions Can Result in Hydrate Plugs



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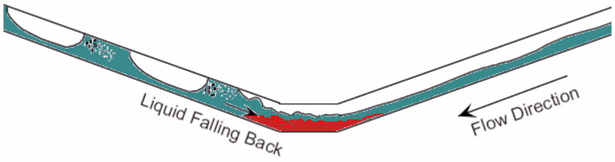
Three-Phase Flow Effects ...

- Flow Assurance:
  - Emulsions
    - Phase Distribution Can Change Continuous Phase and Liquid Characteristics



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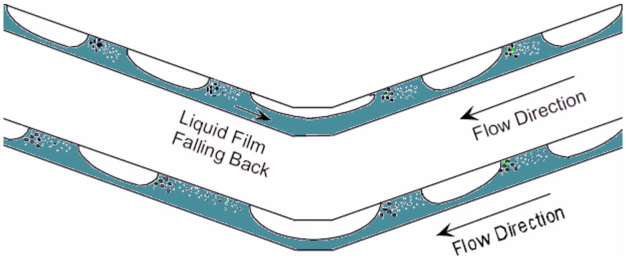
Three-Phase Flow Effects ...

- Flow Assurance:
  - Paraffin Deposition
    - Change in Water Wettability of Pipe Affects Diffusion of Wax Molecules
    - Change in Heat Transfer Characteristics



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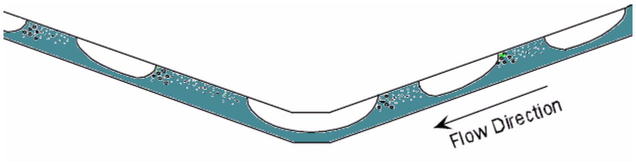
Three-Phase Flow Effects ...

- Flow Assurance:
  - Corrosion
    - Changes in Slug Length and Frequency
    - Water Wet or Oil Wet Pipe?
    - Accumulation of Water at Low Spots



- Prevention of Flow Assurance Problems
  - Delivery and Distribution of Chemicals

Experimental Study

Test Facility

- Change in Test Facility:
  - Previously Run By Atmaca (2007)
  - Facility in Running Condition
  - Relatively Small Modifications Required for Hilly-Terrain Study

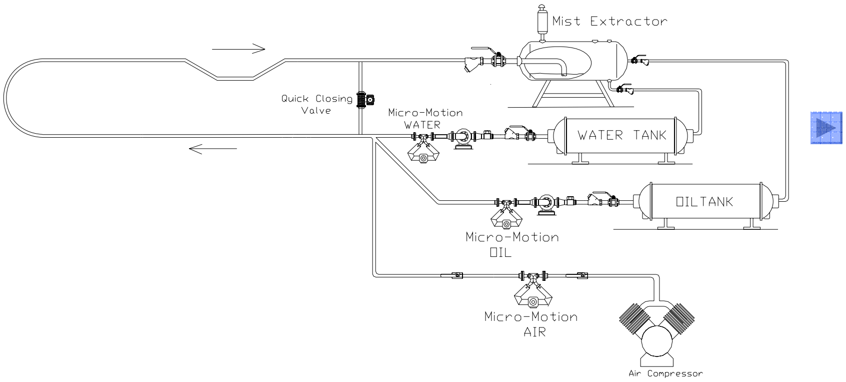
Experimental Study …

Test Facility

- Modified GOW Facility:
  - 69-m (226-ft) Long
  - 50.8-mm (2-in.) ID Pipes
  - Single Hilly-Terrain Unit of 9.7-m (32-ft) Long Downhill Followed by 1.5-m (5-ft) Long Horizontal and 9.7m (32ft) Long Uphill Sections (L/D=413)
  - ±1°, ±2°, ±5°of Inclination Angles

Experimental Study …

Experimental Study …



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Experimental Study …

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Experimental Study …

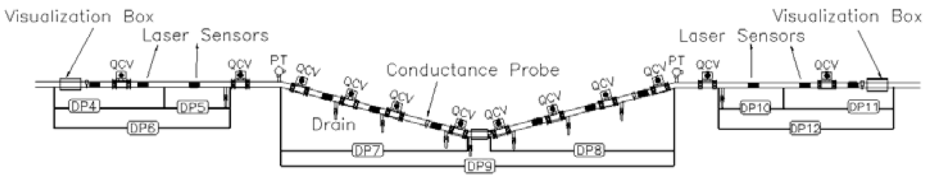
Experimental Study …

Water Pump

Oil Pump

Experimental Study …

Test Section



Experimental Study …

Test Section

Experimental Study …

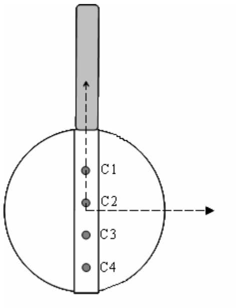
Instrumentation

- Pressure & Differential Pressure Transducers
  - Pressure Drop
  - Identification of Flow Patterns
- Laser Sensors & Quick-Closing Valves
  - Slug Flow Characteristics
  - Average Gas, Oil, Water Holdups

Experimental Study …

Instrumentation

- Conductance Probes
  - Phase Determination at a Point



Insertion Type
Multi-point Probe

Experimental Study …

Instrumentation

- High-Speed Video System
  - Identification of Flow Patterns
  - Slug Characteristics
  - Oil-Water Mixing Status

Experimental Study …

Test Fluids

- Air - Mineral Oil - Water
- Tulco Tech-80 Mineral Oil
  - API: 33.2°
  - Density: 858.75 kg/m^3 @ 15.6 °C (60°F)
  - Viscosity: 13.5 cP @ 40 °C (104 °F)
  - Surface Tension: 29.14 dynes/cm @ 25.1 °C (77.2 °F)

Experimental Study …

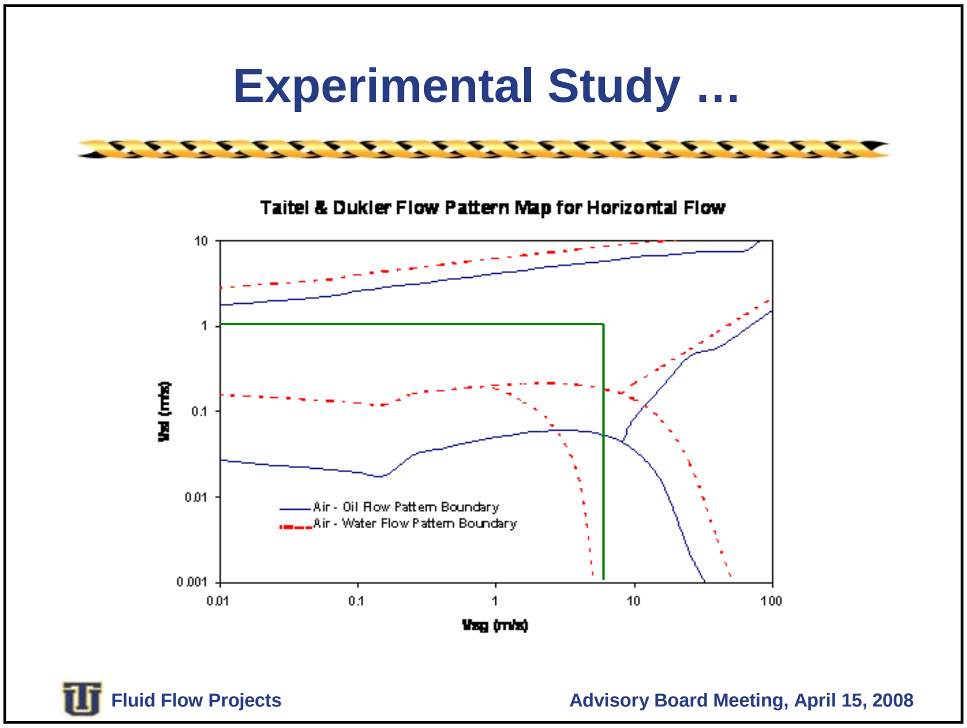
Test Data Acquisition System

- Lab VIEW^{TM} 7.1 Software
- Addition of High-Speed Data Acquisition

Experimental Study …

Testing Ranges

- Superficial Oil Velocity
  - 0.025 – 1.0 m/s
- Superficial Water Velocity
  - 0.025 – 1.0 m/s
- Superficial Gas Velocity
  - 0.1 – 7 m/s
- Water Fraction
  - 20%, 40%, 60%, 80%
  - 0% and 100% for Preliminary Tests
- Hilly-Terrain Unit
  - ±1°, ±2°, ±5°



Experimental Study …

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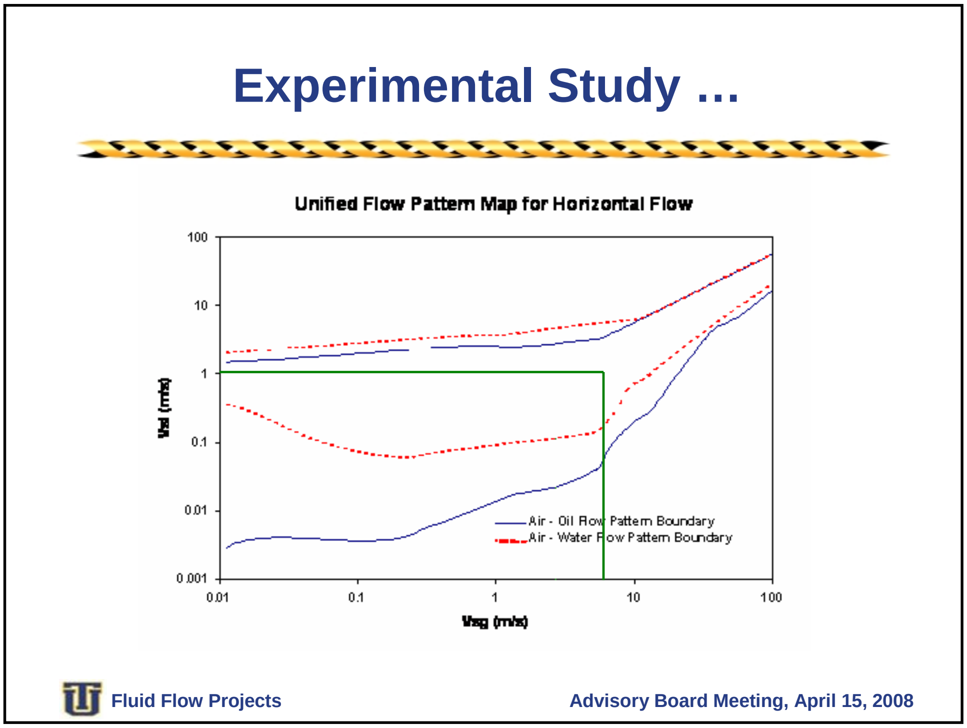

Experimental Study …

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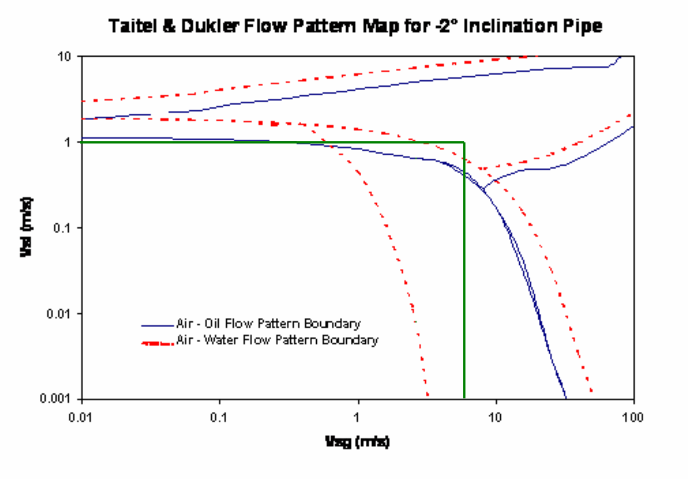
Experimental Study …



Taitel & Dukler Flow Pattern Map for -2° Inclination Pipe

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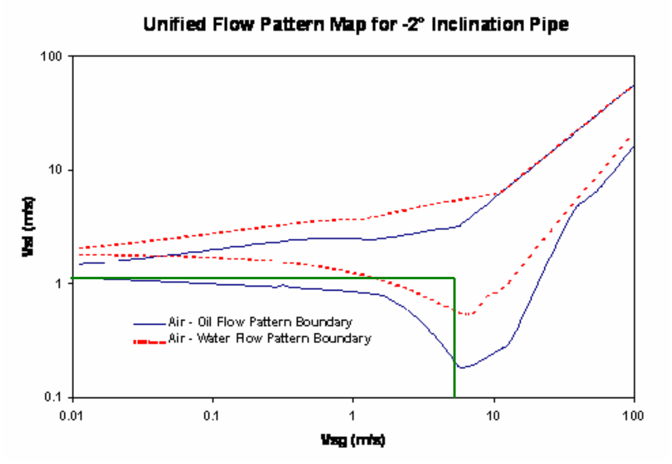
Experimental Study …



Unified Flow Pattern Map for -2° Inclination Pipe

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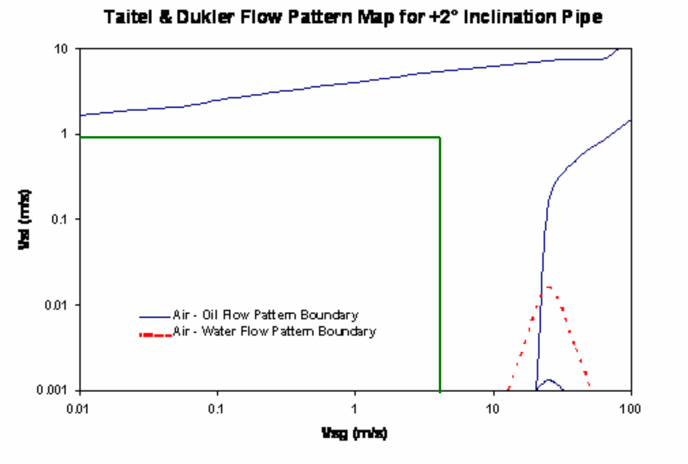
Experimental Study …


Taitel & Dukler Flow Pattern Map for +2° Inclination Pipe

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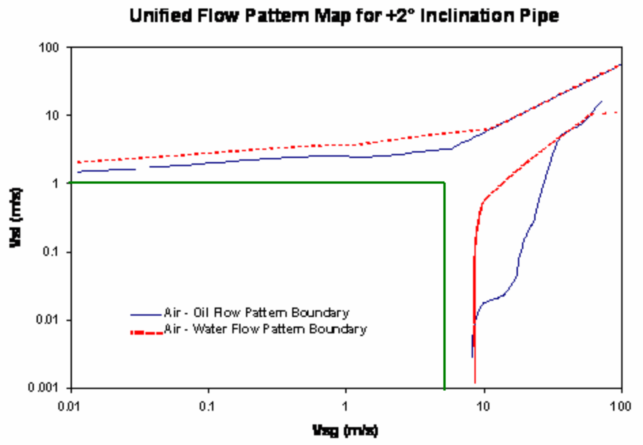
Experimental Study …


Unified Flow Pattern Map for +2° Inclination Pipe

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Experimental Study …

Testing Procedure

- Vary Gas Flow Rate Keeping Oil and Water Flow Rates Constant
- Repeat Above Tests for Several Oil and Water Flow Rates at Constant Water Fraction
- Repeat Above Tests with Different Water Fractions and Inclination Angles

Preliminary Modeling

- Lack of Studies Addressing Three-Phase Gas-Oil-Water Flow in Hilly-Terrain Pipelines
- Significance of Experimental Data
  - Observation of Physical Phenomena
  - Validation of Models
- Comparison of Developed Models with Multiphase Flow Simulator, OLGA®

Preliminary Modeling …

- Identifying Flow Regions of Slug Initiation, Growth and Dissipation with Mixing Status of Liquid Phases
- Development of Closure Models for Three-Phase Flow on:
  - Slug Length/Frequency
  - Translational Velocity
  - Phase Distribution
  - Average Slug Holdup

Preliminary Modeling …

- Investigation of Water Phase at Hilly-Terrain Unit
  - Water Level in Downhill and Uphill Sections of Hilly-Terrain Unit
  - Water Accumulation at Elbow
  - Critical Values

Project Schedule

Facility Modifications	May 2008
Preliminary Testing	June 2008
Ph.D. Proposal Defense	June 2008
Testing	November 2008
Model Development	January 2009
Model Validation	February 2009
Final Report	May 2009

Questions & Comments

Investigation of Three-Phase Gas-Oil-Water Flow in Hilly-Terrain Pipelines

Gizem Ersoy Gokcal

PROJECTED COMPLETION DATES:

Literature Review	Completed
Facility Modifications	May 2008
Preliminary Testing	June 2008
Testing	November 2008
Model Development	January 2009
Model Validation	February 2009
Final Report	May 2009

Objective

The general objectives of this project are:

- to conduct experiments on three-phase gas-oil-water flow in hilly-terrain pipelines,
- to develop closure models for three-phase slug initiation, dissipation and mixing status of phases,
- to validate developed closure models with experimental results.

Introduction

A hilly-terrain pipeline is a pipeline consisting of horizontal, upward inclined, and downward inclined sections. Hilly-terrain pipelines are common in both onshore and offshore production and transportation systems.

In the petroleum industry, slug flow is the most complex and dominant flow pattern in horizontal and near-horizontal pipes. Numerous studies have been carried out on slug flow in pipelines. Although slug flow in horizontal and inclined pipes has been studied extensively, slug flow in hilly-terrain pipelines is still not completely understood. In hilly terrain pipelines, the standard engineering design method has been to divide a pipeline into various sections of constant slopes, and apply steady state flow models to simulate flow behavior in each section. Hydrodynamic slugs generated in uphill sections may or may not decay in following downhill sections, causing uncertainties in pressure behavior. Such configurations can also result in terrain induced slugs that are much longer than those normally encountered in horizontal pipelines. These long slugs often cause operational problems, flooding of downstream facilities, severe pipe corrosion, and structural instability of the pipeline, as well as production loss and poor reservoir management due to unpredictable wellhead pressures.

In the petroleum industry, three-phase gas-oil-water flow can occur in surface gathering lines and sub-sea production lines. The understanding of three-phase flow is crucial for flow assurance problems such as hydrates, emulsions and paraffin deposition. Corrosion and erosion also depend on the characteristics of three-phase flow in pipes. However, very limited amount of work on three-phase flow has been conducted due to the difficulties of oil-water and gas-liquid flow characterizations. Slug flow is also the dominant flow pattern in three-phase pipe flow. This strengthens the significance of slug flow studies for hilly-terrain configurations.

In the open literature, no studies addressing three-phase flow in hilly-terrain pipelines could be found. Since slug flow is such a frequently encountered flow pattern in three-phase flow, a study of slug characteristics for three-phase flow in hilly-terrain pipelines is very crucial for production and pipeline transportation. However, the complexity of slug flow increases from two-phase to three-phase flow. The increased complexity in slug flow necessitates transient solutions, supported by closure models. These closure models should focus especially on the phase distribution throughout the flow, and oil-water interactions, as well as the slug flow characteristics. In this study, these models will be examined and studied.

Experimental Study

Experimental Facility and Flow Loop

The existing two-phase facility that was used by Al-Safran (2003) for a two-phase hilly-terrain study would require many modifications to function in three-phase hilly-terrain flow. Therefore, it was decided at the last ABM, to use the TUFFP facility for gas-oil-water flow due to its three-phase capability and manageable modifications.

The gas-oil-water facility was previously used by Atmaca (2007) for characterization of oil-water flow in inclined pipes. The facility consists of a closed circuit loop with storage tanks, progressive cavity pumps, heat exchangers, metering sections, filters, test section and separator.

For oil and water phases, there are two storage tanks equipped with valves to control the flow rates. Two progressive cavity pumps are maintaining the liquid flow rates. There are manual bypass valves after the pumps to obtain low flow rates, and pressure relief valves for excessive pressure control. Copper-tube type heat exchangers are used to control the temperature of the fluid during the tests. After the heat exchangers, manual bypass valves allow the fluids to be pumped back to the respective tanks.

Two separate 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 the temperatures of the fluids. Oil and water flow through filters after the metering section. At the inlet of the test section gas, oil and water flow through the mixing tee to form the gas-oil-water three-phase mixture. After the fluids flow through the test section, the mixture is directed to the separator where pressure is set at 20 psig.

The test section is attached to an inclinable boom that makes inclined flow in the loop possible. However, during the three-phase hilly-terrain study, the boom will not be used and the part of the flow loop that is mounted on the test section will stay horizontal.

The original test section consists of two 21.1-m (69.3-ft) long runs connected with a U-shaped bend to reduce the disturbance of the flow pattern due to a sharp turn. However, some modifications are needed to both of flow loop and the test section to give enough space for the hilly-terrain branches and instrumentation. The current test section consists of a 21.1-m (69.3-ft) long upstream branch and a 46.7-m (153.2-ft) long downstream branch connected with a 1.2-m (4-ft) long U-shaped PVC bend as shown in Fig. 1. Both of the branches are made of transparent pipes with 50.8-mm (2-in.) diameter.

The upstream branch of the test section consists of a 13.8-m (45.3-ft) long flow developing section (L/D=272.0), two pressure drop sections 5.2-m (17-ft) and 3.3-m (11-ft) long, one long pressure drop section combining the two short sections, and one 5.5-m (18.1-ft) long fluid trapping section (L/D=108). The entire upstream branch is placed on the boom.

The downstream branch of the test section consists of a 13.8-m (45.3-ft) long flow developing section (L/D=272.0), a 6-m (19.7-ft) long horizontal section with two short pressure drop sections 5.2-m (17-ft) and 3.3-m (11-ft) long and one long pressure drop section very similar to the upstream branch, in addition to a 21-m (68.9-ft) long hilly-terrain section (L/D=413.4) followed by a 6-m (19.7-ft) long horizontal section.

The hilly-terrain section simulates a hilly-terrain unit of 9.5 m (31.3 ft) downhill followed by a 1.9 m (6.2 ft) horizontal and 9.5 m (31.3 ft) uphill sections. The inclination angles are ±1°, ±2° and ±5° for the valley configurations. The hilly-terrain section will be heavily instrumented.

The horizontal section immediately downstream of the hilly-terrain section was designed and built similar to the horizontal section immediately upstream of the hilly-terrain section.

The 21.1-m long section of the downstream branch is placed on the inclined boom as in the original gas-oil-water facility. The rest of the downstream branch, which is 25.6 m long, is supported by an aluminum base. Schematic diagram of the test section is given in Fig. 2.

The possibilities of hazards when the facility is operated have been examined. Some hazards have been identified. Protective glass will be installed around the acrylic pipe to provide protection in case of a rupture.

The testing ranges for the three-phase hilly-terrain experiments on the gas-oil-water flow loop are as follows:

- Superficial gas velocity: 0.1-7.0 m/s
- Superficial oil velocity: 0.02-1.0 m/s
- Superficial water velocity: 0.02-1.0 m/s
- Water fraction: 20, 40, 50, 60 and 80%

The lower limits of superficial velocities were decided on by the accuracies of the Micro Motion™ flow meters. The higher limits were set by the pressure gradient and facility limits.

Instrumentation and Data Acquisition

Instrumentations on the transparent pipes measure the operating temperature, pressure, differential pressure, inclination, holdup and spatial distribution of the phases.

Three-phase slug flow in hilly-terrain pipelines is a very challenging subject. Therefore, the gas-oil-water facility is heavily instrumented. The facility can be divided into four segments. The horizontal section at the upstream branch is the first segment. The horizontal section before the hilly-terrain unit, the hilly-terrain unit and the horizontal section after the hilly-terrain unit are segments two, three and four, respectively. Conductance probes, quick closing valves, laser sensors, and pressure and differential pressure transducers will be installed on each segment of the facility.

Absolute and differential pressure transducers will be used to monitor the flow behavior. Absolute pressure transducers are located at the inlet, before and after the PVC bend, before and after the hilly-terrain unit and at the outlet of the pipeline. The aim of the pressure transducers before and after the PVC bend is to monitor and examine the effects of the bend on the flow. Although early studies on gas-oil-water flow showed that the effects of PVC are negligible, an additional developing section for the flow at the downward branch is included in this study. On each defined segment, three differential pressure transducers will be installed. Pressure gradients over segments will be measured for each test.

A high speed video system will be used to identify the flow patterns and determine the oil-water mixing status, in addition to capturing the details of slug characteristics in three-phase flow in hilly terrain configurations. The videos will be taken through visualization boxes.

Laser sensors will be installed on each segment of the facility to obtain translational velocity and slug characteristics, such as slug frequency and slug length. In three-phase gas-oil-water flow, laser sensors will be used instead of capacitance sensors. The laser sensors are much more sensitive to changes in flow characteristics. Preliminary testing on laser sensors to test their ability to respond to three-phase flow was successful. However, the calibration procedure based on changing water fractions is still underway.

Using laser sensors with a high speed data acquisition system makes the analysis of slug characteristics easier and more accurate. Determination of slug frequency is found by dividing the number of slugs detected by one of the laser sensors by the test time.

Times for the slug front and back to travel from the first laser sensor to the second one can be obtained. Since the distance between two sensors is known, the slug front and back velocities can easily be calculated.

If the time difference between a slug front and back passing one of the laser sensors can be determined, slug length can easily be calculated using the translational velocity.

Quick-closing valves will be used for liquid trapping to measure phase fractions and obtain holdup for each flowing condition. The liquid trapped by the quick-closing valves is drained into graduated cylinders to measure the volumes of water and oil phases. There are two quick-closing valves placed in sections upstream of the test section and the horizontal section downstream of the test section. The hilly-terrain test section is divided into seven trapping sections to observe the change in liquid holdups with inclination angles.

Previously designed conductivity probes will be modified. They will consist of four probes across the pipe from top to bottom for determining the location of water phases at four different points. The objective of this configuration is to obtain different data points in the cross-sectional area of the pipe and to determine the continuous phase for all of the flow conditions. Conductance probes will be installed on each segment of the facility to differentiate the conducting water phase from the non-conducting gas-oil phases. There will be a conductance probe at the end of the downstream section and at the end of the upstream section of the hilly-terrain unit.

For data acquisition, Lab View ™ 7.1 will be used. New hardware, including a high speed data acquisition system, will be installed for the laser sensors. The existing program will be updated for three-phase gas-oil-water flow in hilly-terrain studies.

Test Fluids

For the experiments of three-phase flow in a hilly-terrain pipeline, fresh water, air and a refined mineral oil were chosen as the testing fluids. The refined oil, Tulco Tech 80, was chosen based on its easy separation. The physical properties of Tulco Tech 80 are given below:

- API gravity: 33.2°
- Density: 858.75 kg/m^3 @ 15.6°C
- Viscosity: 13.5 cp @ 40°C
- Surface Tension: 29.14 dynes/cm @ 25.1°C
- Interfacial Tension with water: 16.38 dynes/cm @ 25.1°C
- Pour Point Temperature: -12.2°C
- Flash Point Temperature: 185°C

The properties of Tulco Tech 80 were measured by Chevron labs. As shown in Figs. 3 and 4, the density and viscosity changes with temperature at three different flow rates were measured, respectively.

Test Program

A typical test program for gas-oil-water flow in a hilly-terrain pipeline starts with varying the gas flow rate, keeping the oil and water flow rates and water fraction constant. Then, tests will be repeated for several oil and water flow rates at constant water fraction and continue with varying water fraction.

Preliminary Modeling Study

As reported in the previous ABM, the literature review illustrates a lack of studies that address modeling of three-phase gas-oil-water flow in hilly-terrain pipelines. Therefore, the experimental work plays a significant role in the modeling study. The following ideas that will create the fundamentals for modeling will be clarified and extended with the inclusion of experimental results. The resulting models will be validated with experimental data and compared with a multiphase flow simulator, OLGA®.

- In the previous studies of two-phase hilly-terrain pipelines, different cases of flow were identified for slug dissipation, initiation and growth along the hilly-terrain section (Al-Safran, 2003). In the three-phase study, these flow cases will be improved by including the mixing status of oil and water.

- Three-phase gas-oil-water slug flow will be observed in the experiments with changes in inclination angle and water cut. Using the experimental findings, closure models for slug length and frequency, translational velocity, slug holdup and phase distributions will be investigated.

- Existing two-phase slug initiation and dissipation models will be modified for three-phase gas-oil-water flow.

- Water level in downward and upward flow in the hilly-terrain section will be analyzed and modeled.

- Accumulation of water at low spots in pipelines is can come serious corrosion and hydrate problems. At the elbow of the hilly-terrain unit, the water accumulation and critical values of mixture velocity to sweep the water phase will be studied with different inclination angles, water cuts and mixture velocities.

Near Future Studies

Modifications to the facility and instrumentation are expected to be finished by May 2008. The new devices installed in the facility will be calibrated to check their functionality. Their respective calibration curves will be created and included in the DAQ software. Previous instruments being used be recalibrated and tested in the DAQ program. Preliminary testing is expected to begin by June 2008.

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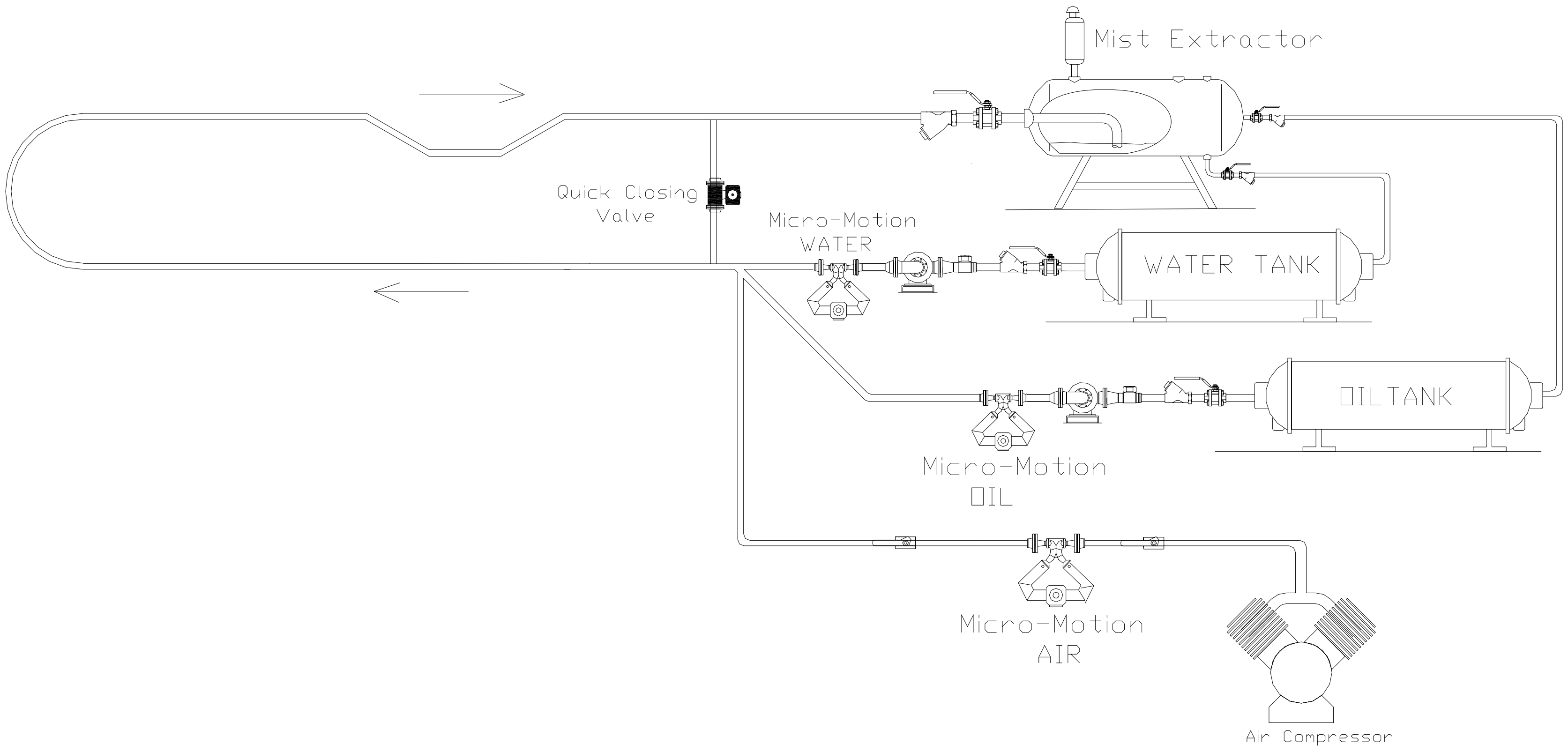


Figure 1: Gas-Oil-Water Facility Schematic

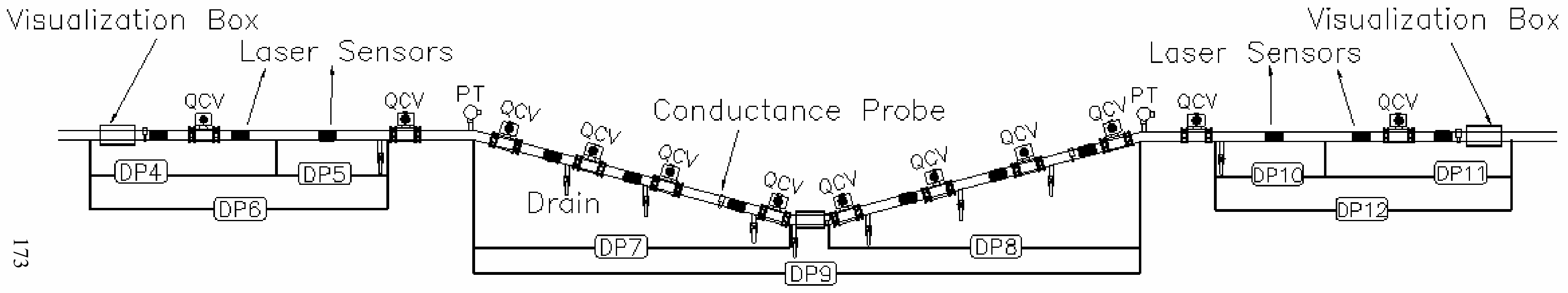


Figure 2: Schematic of Downstream Branch of Test Section

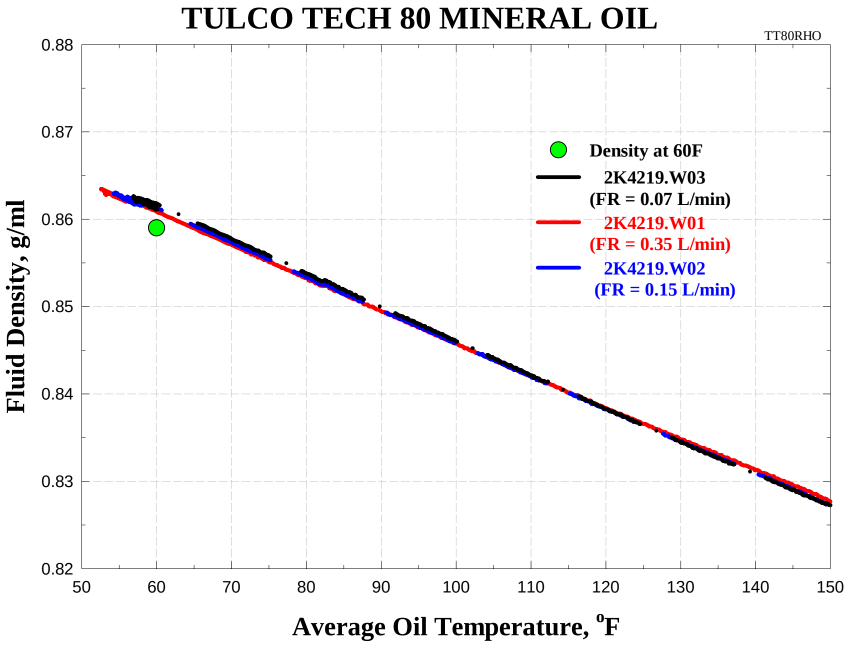


Figure 3: Tulco Tech 80 Oil Density vs. Temperature

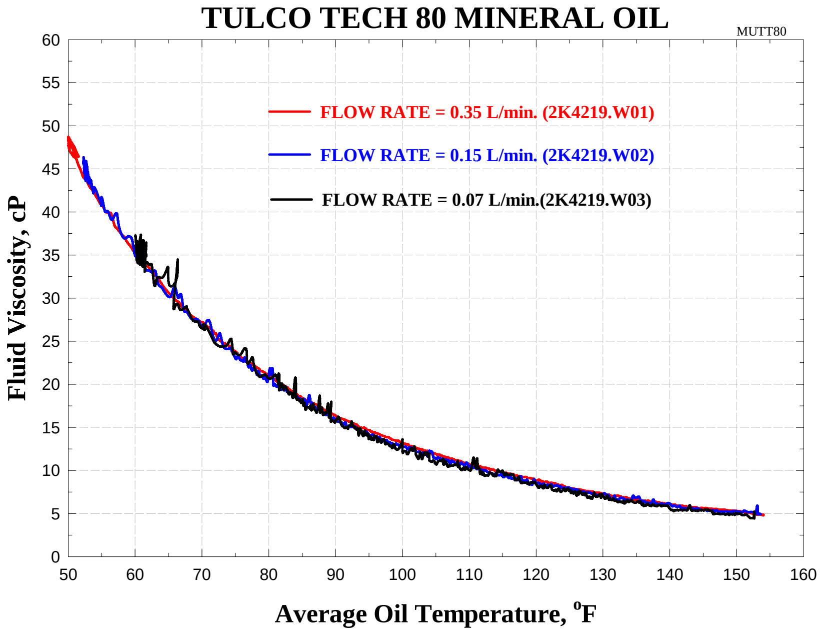


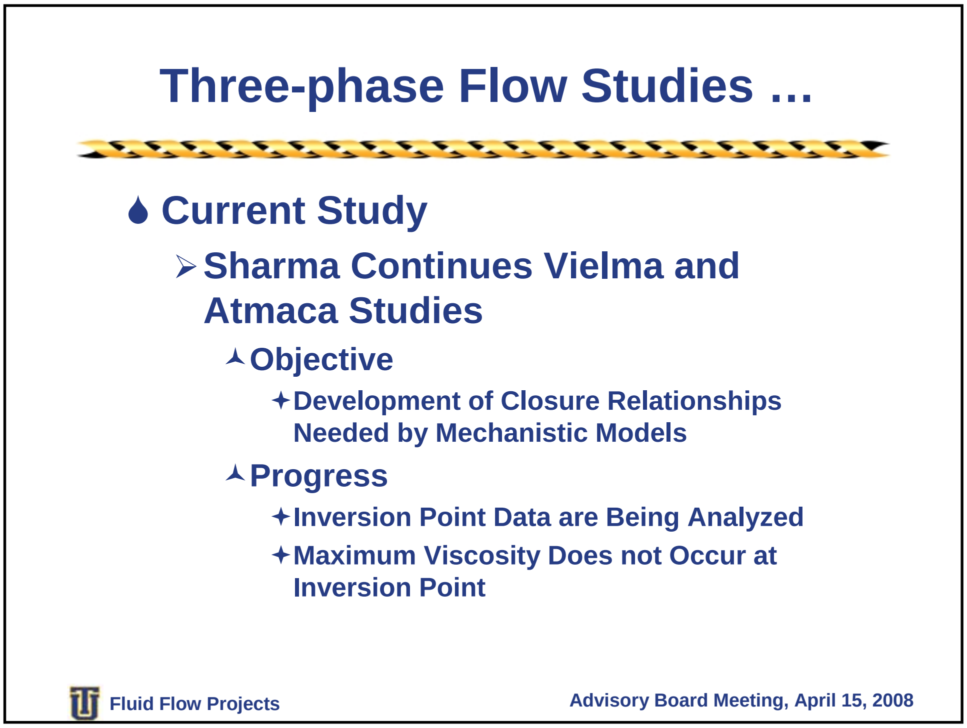
Figure 4: Tulco Tech 80 Oil Viscosity vs. Temperature

Three-phase Flow Studies

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

Three-phase Flow Studies …

- Past Studies …
  - Three-phase
    - Keskin (2007), Experimental Horizontal Three-phase Study
    - Zhang and Sarica (2005), Three-phase Mechanistic Model Development
    - Indicated Need to Conduct More Research on Oil-Water Flow
  - Recent Oil-Water Studies with Emphasis on Droplets
    - Vielma (2006), Horizontal Flow
    - Atmaca (2007), Inclined Flow



Three-phase Flow Studies …

- Current Study
  - Sharma Continues Vielma and Atmaca Studies
    - Objective
      - Development of Closure Relationships Needed by Mechanistic Models
    - Progress
      - Inversion Point Data are Being Analyzed
      - Maximum Viscosity Does not Occur at Inversion Point

Fluid Flow Projects

A Study on Oil-Water Flow Closure Relationships

Anoop Kumar Sharma

Advisory Board Meeting, April 15, 2008

Outline

- Objectives
- Literature Review
- Research Progress
- Near Future Tasks

Objectives

- Identify and Understand all Present Oil-Water Flow Models and Closure Relationships
- Modify or Develop New Closure Relationships for Existing Models for Better Predictions
- Develop New Model if Necessary

Literature Review

- Arirachakaran (1989)
  - Extensive Experimental Study on Horizontal Oil-water Flow for Different Viscosities of Oil
  - Presented Model to Predict Pressure Drop for Both Segregated and Dispersed Flow
  - Developed Correlation for Water-Oil Inversion Point

Literature Review…

- Brauner (1989, 1998, 2001, 2002)
  - Presented Simple Model for Liquid-Liquid Segregated Flow (1989)
  - Developed Two-Fluid Model Considering Curvature Effect of Interface (1998)
  - Suggested a Unified Approach for Predicting Transition to Dispersed Flow for Liquid-Liquid Systems (2001)

Literature Review…

- Brauner (1989, 1998, 2001, 2002)
  - Conducted Theoretical Study About Two-Phase Liquid-Liquid Flow Modeling and Control (2002)

Literature Review…

- Trallero (1995) – TUFFP
  - Experimental and Theoretical Study on Oil-Water Horizontal Flow
  - New Flow Pattern Classification
    - Segregated-Dispersed
  - Developed Mechanistic Model for Stratified Flow

Literature Review…

- Flores (1997) – TUFFP
  - Oil-Water Flow in Vertical and Deviated Wells (90º, 75º, 60º, 45º from Horizontal) to Identify and Characterize Flow Patterns
  - Modeled Flow Pattern Transitions, Pressure Drop and Holdup

Literature Review…

- Alkaya (2000) – TUFFP
  - Experimental and Theoretical Study on Horizontal and Inclined Oil-Water Flow
  - Modified Two-Fluid Model for Better Prediction by Presenting New Approach
    - Dispersion of Oil in Water and Water Flow Pattern, and Dispersion of Water in Oil and Oil Flow Pattern are Treated as Segregated Flow

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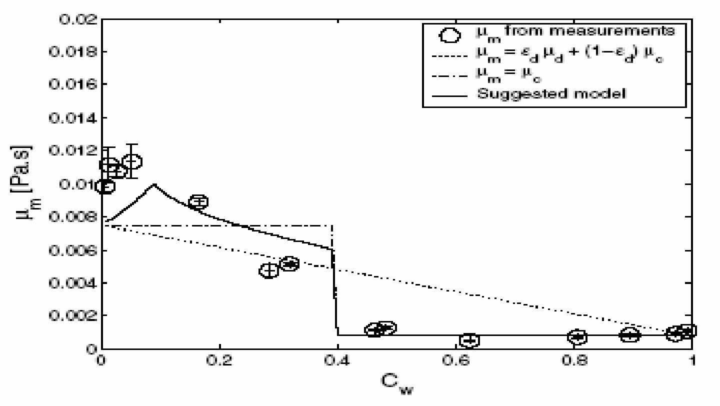
Literature Review…

- Zhang (2005)
  - Unified Model for Three-Phase Gas-Oil-Water Pipe Flow
  - Closure Relationships for Mixing and Inversion Point are Proposed for Describing Distribution Between Liquid Phases

Literature Review…

- Guet (2006)
  - Inverse Modeling for Dispersed Phase Flow to Predict Flow Rate
  - New Approach Used to Model Viscosity Data

Literature Review…



Guet (2006) experimental data and modeling approach

Literature Review…

- Vielma (2006) – TUFFP
  - Acquired Detailed Experimental Data Including Pressure Gradient, Holdup, Phase Distributions, Droplet Size Distribution and Velocity Fields in Horizontal Pipes
  - Developed Empirical Correlation to Predict Sauter Mean Diameter (SMD)

Literature Review…

- Atmaca (2007) – TUFFP
  - Acquired Detailed Experimental Data Including Pressure Gradient, Holdup, Phase Distributions and Droplet Size Distribution in Horizontal and Slightly Inclined Pipes (-5° to +5°)

Literature Review Summary

- Most of the Studies on Oil-Water Flow are Experimental
- Data Mainly Deal with Holdup and Pressure Drop
- Limited Work on Mechanistic Model Development for Oil-Water Flow
- Dispersed Flow is Given Less Attention Than Segregated Flow Modeling

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Research Needs

- Assessment of Current Models by Checking against Experimental Data
- Improvement of Current Models through Development of Better Closure Relationships
- Development of New Model, if Necessary

Research Progress

- All Available Models have been Studied, Mainly Addressing Pressure Drop Predictions
- Close Look Given to Unified Model
- Data Obtained at TUFFP are being Used for Study

Research Progress…

- Areas of Improvements in Unified Model
  - Better Relationship for Interfacial Shear Stress (Stratified and Stratified Mixing)
    - Interface shape
  - Assumption of Fully Mixed Dispersed Flow
    - Exaggeration of Mixing Status

Research Progress…

- Areas of Improvements in Unified Model
  - Unified Model Uses Brinkman Emulsion Viscosity Correlation
    - Mixtures Do not Act as Emulsions for All Water Fractions

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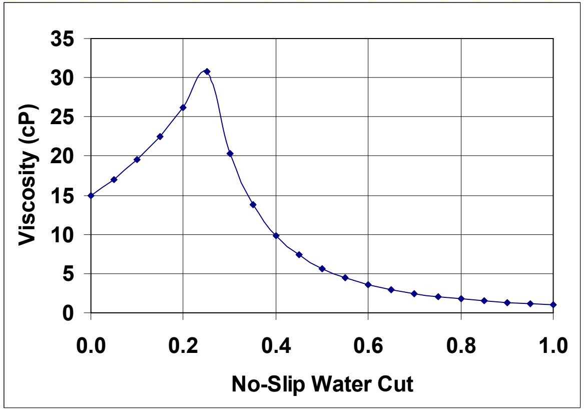
Research Progress…

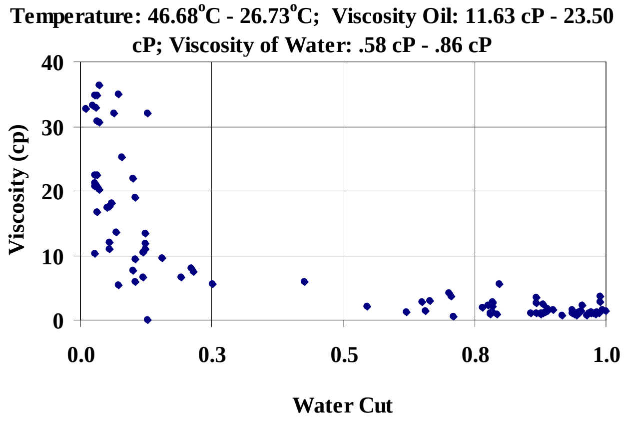


Viscosity versus no-slip water cut using Brinkman correlation

Research Progress…

- Viscosity Calculation
  - All Dispersed Flow Data From Atmaca (2007)
  - Haaland (1983) Friction Factor Relation
  - Pipe Roughness Taken as 10^{-5}m

Research Progress…



Mixture viscosity versus water cut (Atmaca, 2007) experimental data

Near Future Tasks

- New Closure Relationships and Model Modifications by September 2008
- Validating Modified Model Against Experimental Data Available by January 2009
- Final Report and Thesis by May 2009

Questions & Comments

A Study on Oil-Water Flow Closure Relationships

Anoop Kumar Sharma

PROJECT COMPLETETION DATES:

Literature Review..April 2008
Model Development…..September 2008
Model Validation…………..………………………………….................................January 2009
Final Report and Thesis……………………..……………………………………..May 2009

Objectives

The objectives of this study are to find better closure relationships for oil-water flow that can be implemented in the TUFFP Unified Model and any other mechanistic model to improve oil-water flow predictions. Existing models and closure relationships will be identified and tested against available experimental data. Existing models will be modified by implementing new or modified closure relationships and, if necessary, a new model will be developed.

Introduction

The flow of two immiscible liquids is encountered in a diverse range of processes and equipment, particularly in the petroleum industry, where mixtures of oil and water are often transported in pipes over long distances. Accurate prediction of oil-water flow characteristics, such as flow pattern, water holdup and pressure gradient is important in many engineering applications. However, despite their importance, liquid-liquid flow has not been explored to the same extent as gas-liquid flow. Liquid-liquid systems are characterized by low-density ratios. The density difference between the phases is relatively small. However, the viscosity ratio encountered can extend over many orders of magnitude. Moreover, oils and oil-water emulsions can show either a Newtonian or non-Newtonian rheological behavior. Therefore, concepts always related to gas-liquid two-phase flow cannot be readily applied to liquid-liquid systems.

Literature Review

Arirachakaran (1983) collected extensive experimental data for oil-water flow in horizontal pipes for a wide range of oil viscosities. Pressure gradient prediction models were developed for both stratified and dispersed flows, assuming a smooth interface for stratified flow and full dispersion for dispersed flow. Experimental oil-water flow pattern maps were also developed. Moreover, a new correlation was developed to predict the inversion point of oil-water dispersions.

Brauner and Maron (1989) developed a simple two-phase liquid-liquid stratified flow model. Brauner et al. (1998) developed a model for stratified flow which also included the effect of a curved interface. Brauner (2001) suggested a unified approach for predicting the transition to dispersed flow for liquid-liquid systems for all inclinations. This approach is based on revised models for predicting the maximum drop size in a turbulent field, which accounts for the holdup of the dispersed phase. Brauner (2002) conducted a theoretical study of two phase liquid-liquid flow modeling and control. She combined several studies related to the subject and presented a general description of the flow patterns present in liquid-liquid flow with all the modeling approaches.

Alkaya (2000) conducted both theoretical and experimental studies of inclined oil-water flow. Flow patterns, holdup, and pressure gradients were measured for near-horizontal inclinations (-5 degree to +5 degree). The pressure gradient data were compared against existing pressure gradient prediction correlations, a two-fluid model and a homogeneous model. To fill the gap between experimental and predicted pressure gradients, Alkaya presented a new approach in which the dispersion of oil in water and water flow pattern, and the dispersion of water in oil and oil flow pattern were treated as segregated flow.

Zhang and Sarica (2005) presented a unified model for three phase gas-oil-water pipe flow. In their model, the phase distribution and hydrodynamics are described based on two criteria: gas-liquid flow pattern and oil water mixing status. Closure relationships for mixing and inversion point were proposed for describing the distribution between liquid phases.

Guet et al. (2006) presented a new approach to handle viscosity of an oil-water mixture and suggested using a hybrid water cut dependent model. For a dispersion of oil in water, the mixture viscosity is considered constant and equal to the viscosity of water at that temperature. For a dispersion of water in oil, viscosity is calculated by treating the dispersion as an emulsion when the dispersed phase volume fraction is lower than a critical value, below which it acts like an emulsion. For volume fractions greater than the critical value, viscosity is calculated as a linear function of volume fraction.

A list of some major published experimental studies on oil-water is given in Table 1.

Some other notable studies have also been conducted at TUFFP on oil-water flow. Trallero (1995) conducted extensive experimental and theoretical studies of flow patterns. A new classification of flow patterns was proposed containing segregated flow patterns and dispersed flow patterns. Under these, a total of six flow patterns were identified. Trallero developed a new mechanistic model for stratified flow and performed a force balance between gravity and turbulent fluctuations normal to the axial flow direction for dispersed flow to identify flow pattern transitions from segregated to dispersed flow. Flores (1997) investigated oil-water flow, both theoretically and experimentally, in vertical and deviated pipes with 90^o, 75^o, 60^o, and 45^o inclinations from horizontal. He identified and characterized the flow patterns and modeled the flow pattern transitions, pressure drop and holdup. Vielma (2006) acquired detailed experimental data including pressure gradient, hold-up, phase distributions, droplet size data and velocity fields in horizontal and slightly inclined pipes (-1^o to $+1^o$). An empirical correlation was developed that predicts the Sauter Mean Diameter (SMD). Atmaca (2007) extended Vielma's work to inclined pipes (-5^o to $+5^o$).

Research Progress

All available models for oil-water flow have been studied, mainly addressing pressure drop predictions. The unified model has been carefully studied to find areas of improvements. Data obtained at TUFFP are being used to analyze the present models. Atmaca (2007) showed that the Zhang et al. (2005) model predicts the pressure gradient fairly accurate for stratified flow patterns, but as the superficial velocities of the phases increase, the deviation between the predicted and experimental pressure gradients also increases. A preliminary study shows the following areas of improvement are needed in the unified model.

- Better relationships for interfacial shear stress (stratified and stratified mixing),
- Assumption of fully mixed dispersed flow,
- Unified model uses the Brinkman emulsion viscosity correlation.

The Unified model assumes a plane interface, although a common configuration in liquid-liquid pipe flow is two layers separated by a curved interface. Accounting for the interface curvature may have significant effects on the prediction of holdup and pressure gradient. An extensive study will be carried out to improve the relationship for interfacial shear stress.

The assumption of fully mixed dispersed flow is an exaggeration of the mixing status in dispersed flow. A dispersion of oil in water and water flow pattern and a dispersion of water in oil and oil flow pattern clearly show segregated phases. It would be more accurate to consider and model these flow patterns as two separate segregated phases with one having its own physical properties and the other having mixture properties.

The viscosity correlation is another issue in the unified model. The Brinkman correlation is valid for emulsions. For an emulsion, the dispersed phase should have small droplet sizes in a diluted state in the continuous phase. When the volume fraction of the dispersed phase increases, coalescence plays an important role and the maximum drop size increases significantly. In such a case it will no more remain an emulsion and the Brinkman correlation will not hold true anymore. It will overestimate the viscosity of the dispersion. In the spirit of the model suggested by Guet (2006), a hybrid water-cut model should be used where emulsion viscosity correlateions should only be used for water cut (no slip) values below a critical water cut where it will act like an emulsion. Figures 1-3 show the Brinkman correlation predictions and experimental results and the Guet approach, respectively. For calculation of viscosity from experimental data, the Haaland (1983) friction factor relationship is used and a roughness factor is taken as 10^{-5} as suggested by Guet for Perspex smooth pipe. It can easily be seen in these graphs that application of the Brinkman correlation for all the water cuts is not a good approach. There is also a clear aberration in the data due to temperature effect on viscosity and dispersion characteristics. The temperature is varying from 46.7°C to 26.7°C for the experimental data plotted in fig 2 and, correspondingly, the viscosity of pure oil is varying from 11.63 cP to 23.50 cP and the viscosity of water is varying from 0.58 cP to 0.86 cP, respectively. These viscosities issues will be addressed in greater depth.

Near Future Tasks

The following tasks will be conducted in the near future:

- Proposal of new closure relationships and model modifications by September 2008.
- Testing the modified model against the experimental data by January 2009.
- Final report and Thesis by May 2009.

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Table 1: Summary of Oil Water Studies

Authors	Inclination Angle (º)	d(cm) Pipe Material	μ_o/μ_w	ρ_o/ρ_w	Additional Measurements	Observed Flow Patterns
Arirachakaran et al. (1989)	0	3.81, 2.54 Steel with a Lexan Portion			dP/dL Hw	S, Mo, Mw, Ao, Aw, Io, Iw, Do, Dw
Trallero (1995)	0	5.08 Acrylic	29.7	0.852	dP/dL Hw	S, SM, DO/W & W, DO/W, DW/O, DW/O & O/W, DW/O & W
Flores (1997)	+45,+60, +75, +90	5.08 Acrylic	20	0.858	dP/dL Hw (conductivity probe)	DO/W CT,DO/W PS, VF DO/W, DW/O CC, VFDW/O, Churn TF
Nädler & Mewes (1997)	0	5.9 Perspex	35-28	< 1% difference between ratios	Phase Inversion (In-line conductance cell) dP/dL	S,SM, DO/W & W, DO/W, DW/O, DW/O & O/W & w, DW/O & W
Soleimani et al. (1999)	0	2.54 Stainless Steel	1.8	0.8	dP/dL Hw Volume fraction Phase distribution (high frequency impedance probe and a gamma densitometer system)	S,SM, DO/W & W, DO/W, DW/O, DW/O & O/W, DW/O & W
Angeli & Hewitt (2000)	0	Two 2.54 cm Stainless Steel and Acrylic Resin	1.8	0.8	Droplet size	Dispersed flow
Alkaya (2000)	0,±0.5, ±1, ±2, ±5	5.08 Acrylic	18	0.854	dP/dL Hw	S,SM, DO/W & W, DO/W, DW/O, DW/O & O/W, DW/O & W
Lum et al. (2001)	0,+5,+10	3.8 Stainless Steel with an acrylic section	6.18	0.83	dP/dL Hw Phase continuity (conductivity probe) Phase distribution (impedance probe)	S, SM, DC, FDF PF
Lovick and Angeli (2004)	0	3.8 Stainless Steel	6.74	0.83	Droplet Size Velocity Profiles	DO/W & W, DO/W, DW/O, DW/O & O/W, DW/O & W
Rodriguez and Oliemans (2005)	±5, ±2,-1.5, 0, 1	8.28 Steel	9.38	0.78	Hw and Ho (2 gamma ray densitometers) dP/dL	S,SM, DO/W & W, DO/W, DW/O, DW/O & O/W, DW/O & W

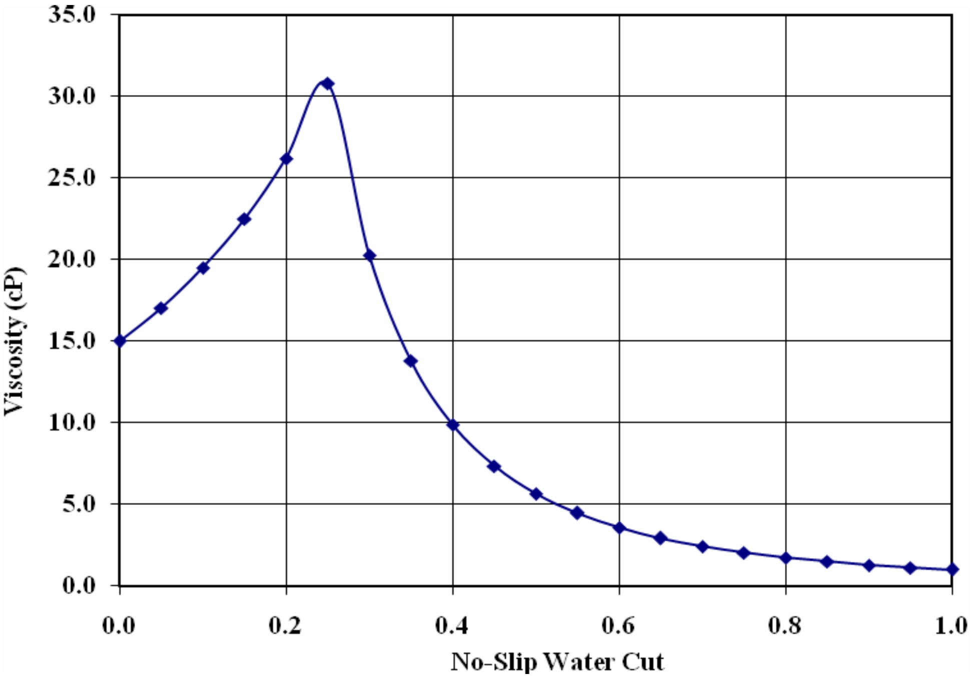


Figure 1: Viscosity versus no-slip water cut using Brinkman correlation

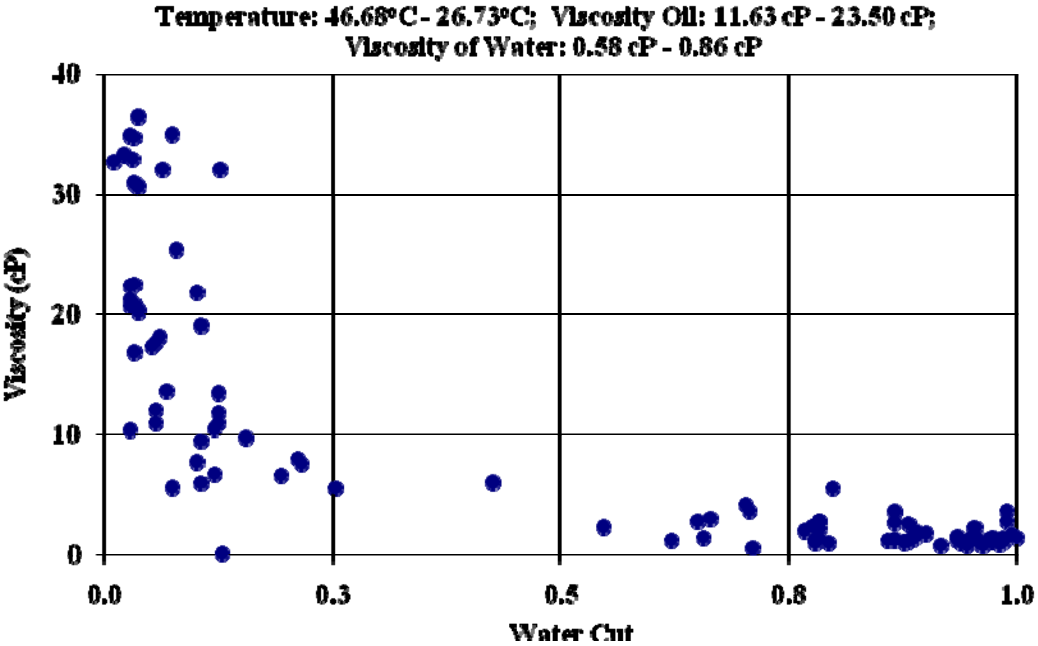


Figure 2: Normalized viscosity versus no-slip water cut (Atmaca (2007)) experimental data

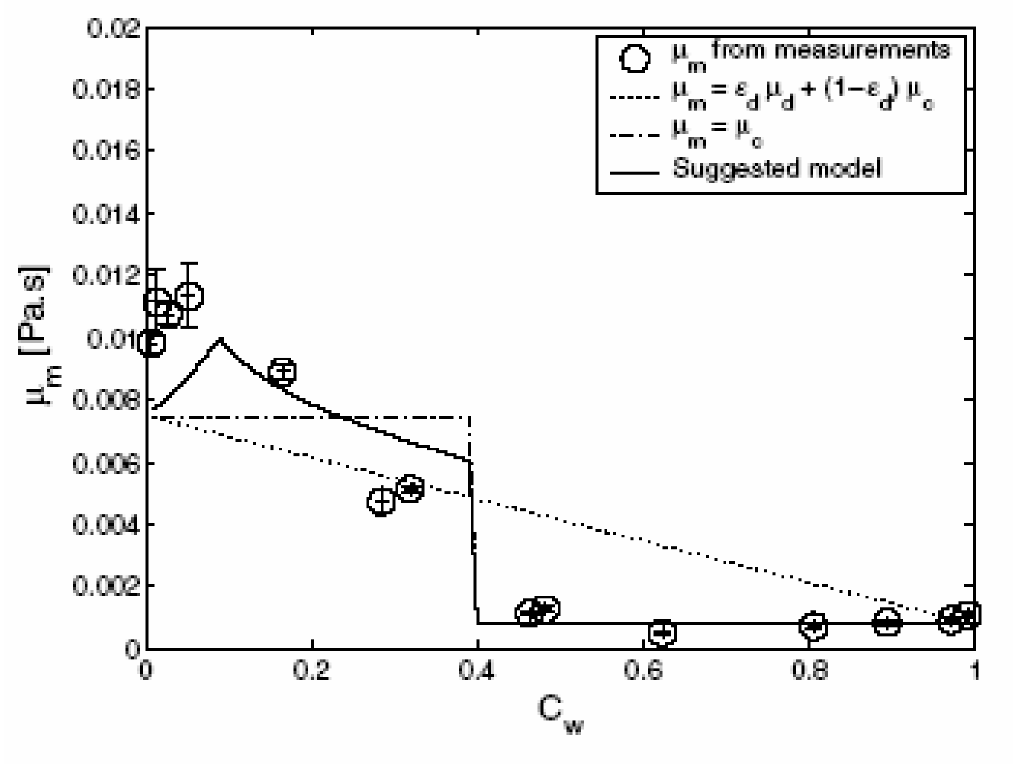


Figure 3: Guet (2006) experimental data and modeling approach

Up-Scaling Studies

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

Up-Scaling Studies …

- Current Project
  - Construction of a New High Pressure, Large Diameter Facility
  - Extension of Low Liquid Loading Study to High Pressures is Envisioned as the First Study

Up-Scaling Studies …

- Status
  - Preliminary Design is Complete
    - Operable with both Nitrogen and Natural Gas
  - Safety Concerns Raised With Utilization of Natural Gas
  - Professional Outside Evaluation of the Design is Sought
  - Fire Marshall was Contacted
    - Informal No Concern Response
  - Long Lead Item Equipments Such As Compressor have been Ordered
  - Generator is Already Delivered

Up-Scaling Studies …

- Near Future Activities
  - Completion of Professional Design
  - HAZOP Study
  - Start of Construction

Fluid Flow Projects

Up-scaling Studies in Multiphase Flow

Abdel Al-Sarkhi

Advisory Board Meeting, April 15, 2008

Outline

- Objectives
- Introduction
- 6 in. Diameter High Pressure Facility
- Special Instrumentation
- Safety Issues
- Other Consideration
- Capital Cost &Time Table
- Proposed Initial Project

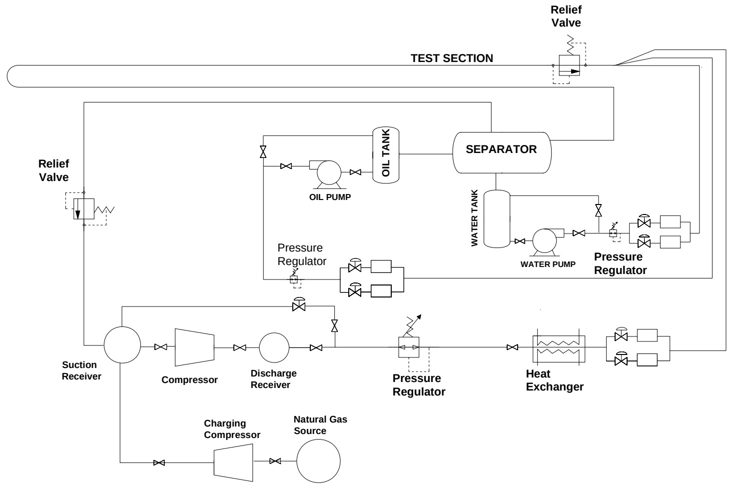
Objectives

- Investigate Effect of Pipe Diameter and Pressure on Multiphase Flow Behavior
- Verify and Improve Models / Correlations Against New Data

Introduction

- Pressure and Pipe Diameter Affect Flow Behavior in Multiphase Flow Significantly
- Most of Investigations are for Low Pressure and Small Diameter Conditions

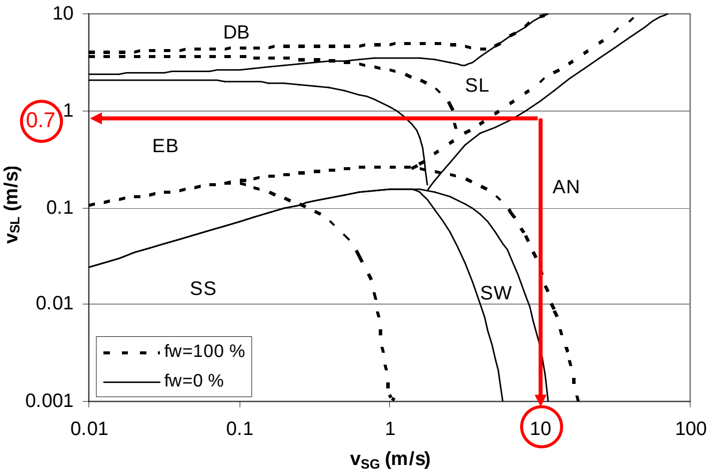
High Pressure Facility



Fluids

- Gas Phase –
  - Nitrogen
  - Tulsa City Natural Gas
- Oil Phase - Tulco Tech-80 Mineral Oil
- Water Phase - Tulsa City Water

Flow Pattern Maps

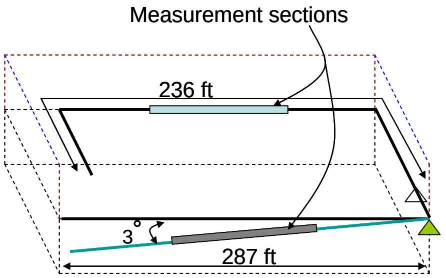


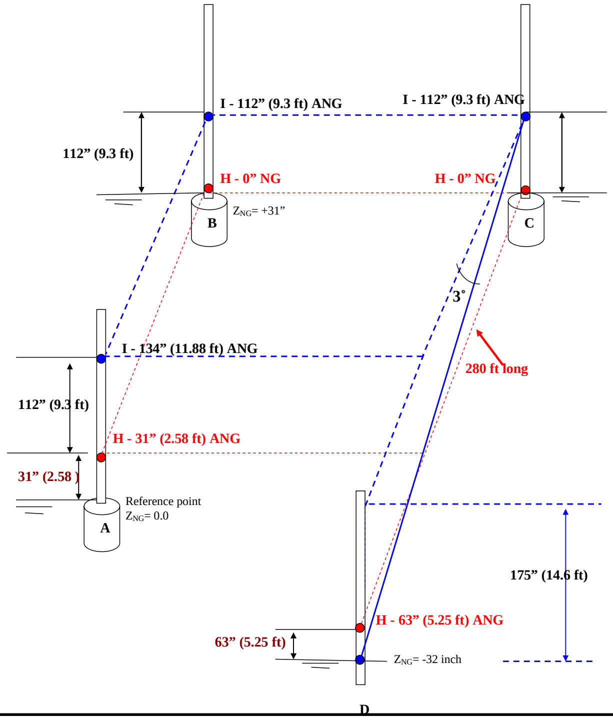
Operating Range

- Operating Pressure = 500 psig
- $v_{SL,\ max}$=0.7 m/s; $v_{SG,\ max}$=10 m/s
- f_w Between 0 and 100 %
- $q_{G,\ max}$ = 18 MMSCFD
- $q_{L,\ max}$ = 200 GPM
- Separator 54" x 10' @ 600 psig

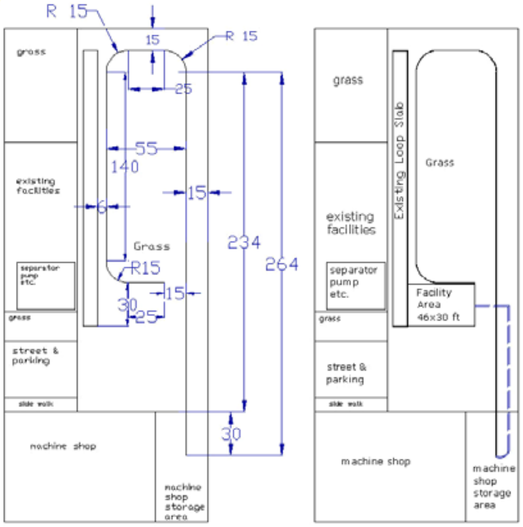
Test Section

- Total Length = 523 ft
- Inclined Part Length = 287 ft
- ±3° Inclination
- 15 ft Bend Radius





Flow Loop Layout and Space Available (Dimensions in Feet)

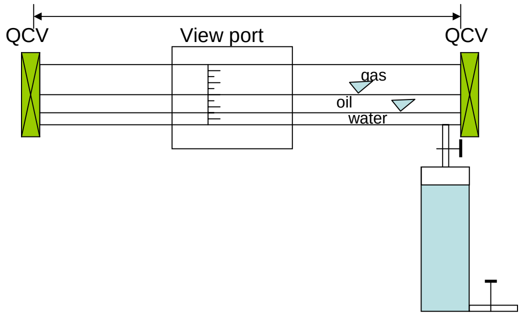


Basic Instrumentation

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

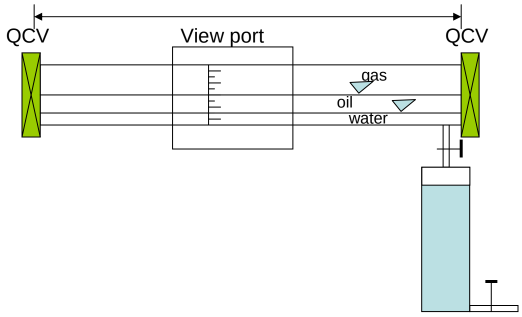
Special Instrumentation

- Total Liquid Holdup
  - Quick Closing Valve
  - Viewing Window (measure the liquid height)
  - Two Lasers Sensor (trial)
  - Conducting Probe for Water Height (?)



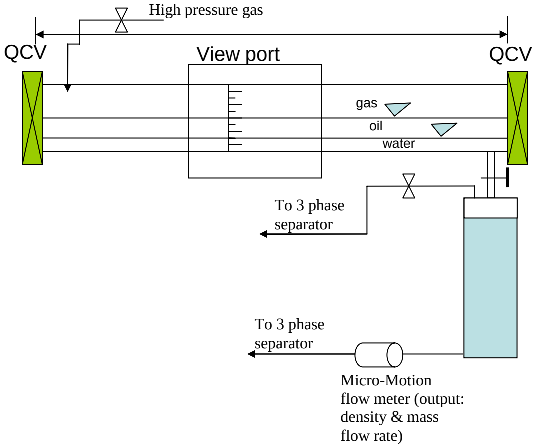
Special Instrumentation

- Oil/Water Holdup
  - Quick Closing Valve
  - High Pressure to flush liquid out
  - Wait for Separation of Oil and Water
  - Multiple Point Densitometer to Get the Level
  - Push the Liquid Back to Separator Using Gas Line



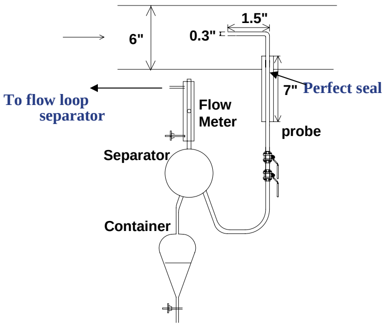
Special Instrumentation (Suggested By Fan)

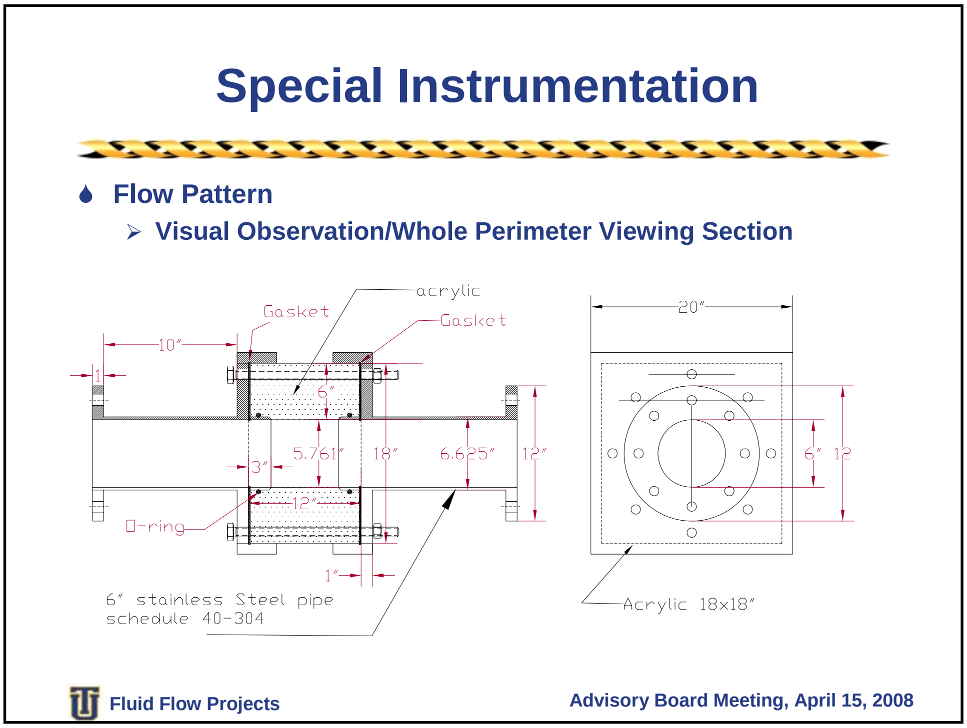
- Oil/Water Holdup



Special Instrumentation

- Liquid Entrainment
  - Iso-kinetic Probe High Pressure Rating
  - Gas Outlet to Separator



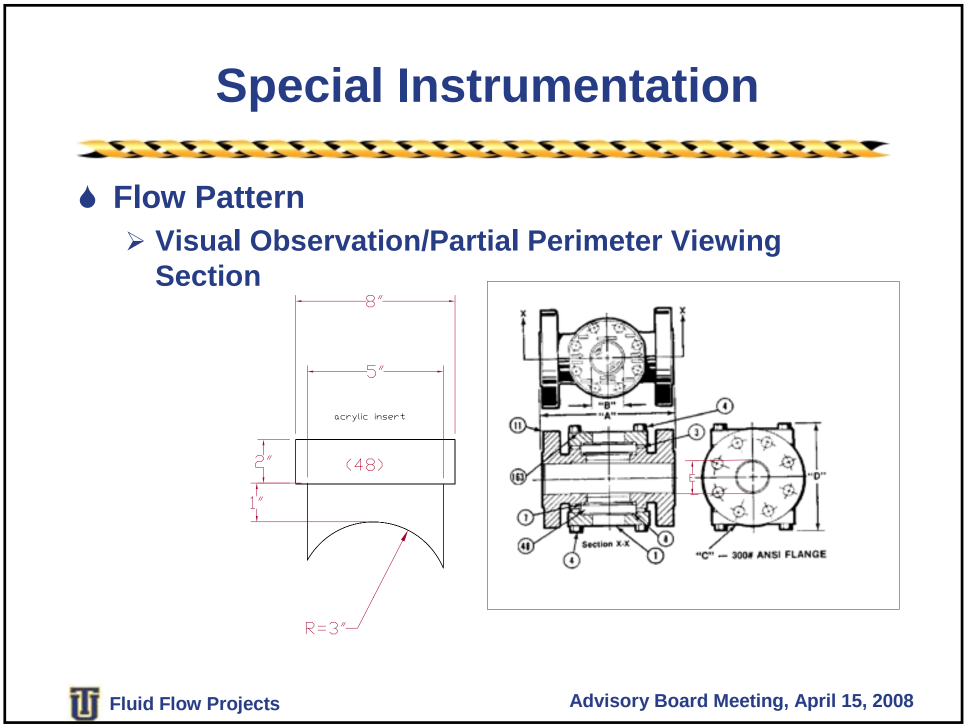


Special Instrumentation

- Flow Pattern
  - Visual Observation/Whole Perimeter Viewing Section

Fluid Flow Projects

Advisory Board Meeting, April 15, 2008



Special Instrumentation

- Flow Pattern
  - Visual Observation/Partial Perimeter Viewing Section

Fluid Flow Projects

Advisory Board Meeting, April 15, 2008

Safety Issues

- Residential Area Is Located on the East and North Side of the Pipeline Next to the Wooden Fence
- University Machine Shop Is Located on the South Side of the Pipe Line Area
- An onsite Control Room
- Finding the Right Safety Regulations

Safety Issues…

- Nitrogen as a Transition State
  - To Master/ Control All Sections at High Pressure for Issues of Seal and Instrumentation Connections Using Less Hazardous Gas
  - To Train Our Staff and Students and Establish a Procedure for Using the High Pressure Facility
  - To Obtain Data at Higher Gas Density

Nitrogen-Solubility

- Is the Flow of Nitrogen Similar as to That of Natural Gas?
- Solubility of Natural Gas
  - About 4 Times That of Nitrogen on Mole Bases
  - Twice on Mass Bases Due to Difference in Their Molecular Weights (16/28 gr/mole).
- Solubility will Mainly Affect Viscosity of Flowing Liquid
- Flow Behavior will be Almost Comparable
- Regarding Entrainment Fraction
  - Main Factor is Difference in the Gas Density at the Operating Pressure Which will be Recorded

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Other considerations

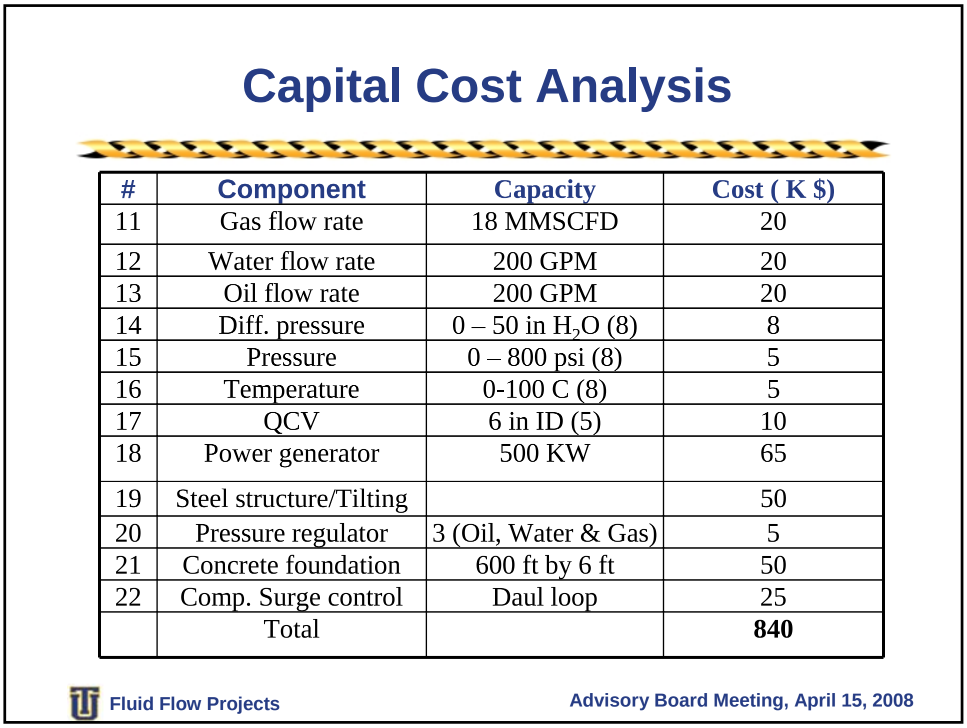
- Insulating the Pipe for Better Temperature Control
- Stainless Steel Material will be Used (Previously Carbon Steel Was Suggested)

Near Future Plan

- Efforts have been Made to Get a Consulting Company Opinion on Safety and Operability
- Local Fire Marshall is in Process of Researching Appropriate Rules, Regulations and Permits
- Enserca Engineering is the Engineering Company That has Agreed to Work With Us Through Permitting and Design Stage of The Project
- Additive Systems Inc. will Handle a Significant Portion of The Construction

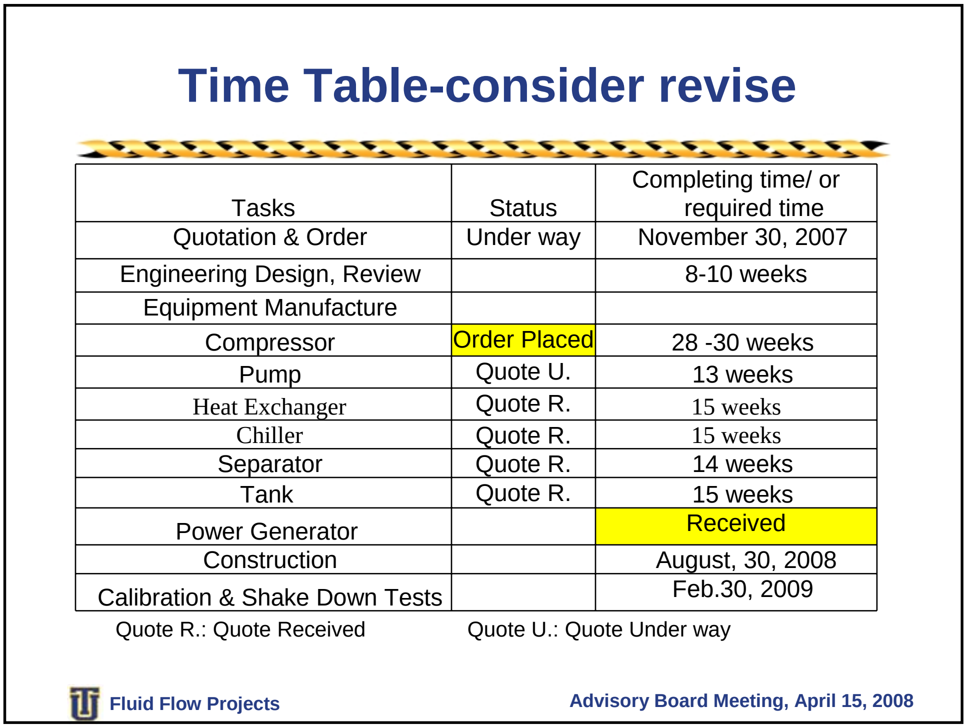
Capital Cost Analysis

#	Component	Capacity	Cost (K $)
1	Compressor	18 MMSCFD	242
2	Heat Exchanger	720,000 BTU/HR/Pass	18
3	Chiller	90 ton	60
4	Safety Valves	2	2
5	Water pump	200 GPM	20
6	Oil pump	200 GPM	20
7	Separator	54" x 10' x 600	36
8	Water tank	1200 gallon	33
9	Oil tank	1200 gallon	33
10	Pipeline (SS)	6-in. ID, 540 ft	90



Capital Cost Analysis

#	Component	Capacity	Cost (K $)
11	Gas flow rate	18 MMSCFD	20
12	Water flow rate	200 GPM	20
13	Oil flow rate	200 GPM	20
14	Diff. pressure	0 – 50 in H_2O (8)	8
15	Pressure	0 – 800 psi (8)	5
16	Temperature	0-100 C (8)	5
17	QCV	6 in ID (5)	10
18	Power generator	500 KW	65
19	Steel structure/Tilting		50
20	Pressure regulator	3 (Oil, Water & Gas)	5
21	Concrete foundation	600 ft by 6 ft	50
22	Comp. Surge control	Daul loop	25
	Total		**840**



Time Table-consider revise

Tasks	Status	Completing time/ or required time
Quotation & Order	Under way	November 30, 2007
Engineering Design, Review		8-10 weeks
Equipment Manufacture		
Compressor	Order Placed	28 -30 weeks
Pump	Quote U.	13 weeks
Heat Exchanger	Quote R.	15 weeks
Chiller	Quote R.	15 weeks
Separator	Quote R.	14 weeks
Tank	Quote R.	15 weeks
Power Generator		Received
Construction		August, 30, 2008
Calibration & Shake Down Tests		Feb.30, 2009

Quote R.: Quote Received Quote U.: Quote Under way

Proposed Initial Project

- Investigation of 2 phase Low Liquid Loading at High Pressures
- Investigation of 3 phase Low Liquid Loading at High Pressures

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Up-scaling Studies

Comments

&

Suggestions

Upscaling Studies in Multiphase Flow

Abdel Al-Sarkhi

Objectives

Scaling up of models based on small diameter and low pressure experimental data to large diameter and high pressure conditions is very important in multiphase flow research studies. Studies with a large diameter facility would significantly improve our understanding (and modeling) of flow characteristics in actual field conditions. Therefore, our main objective in this project is to investigate the effect of pipe diameter and pressures on flow behavior using a large diameter and high pressure flow loop.

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, under high pressure condition is different from those under typical laboratory conditions. It is important to validate the applicability of the models with experimental results obtained for conditions similar to those experienced in a real field.

A new facility with large pipe diameter and high pressure was proposed at the last ABM. With this facility, the effects of pipe diameter and pressure on two-phase and three-phase flow behaviors can be investigated. Experimental data from this facility can be used to evaluate existing models and correlations. New models and closure relationships can be developed if needed.

The New Flow Loop

Fluids

The facility is designed for gas-oil-water three-phase flow. Tulco Tech-80 Mineral oil and Tulsa City water are the liquid phases. The facilities, equipment and instrumentation are designed to have the ability to work with either Natural gas (Tulsa City Natural gas) or Nitrogen. Initially, Nitrogen will be used due to its relatively low safety risk. In fact, Nitrogen has a higher density than natural gas at the same operating condition (see Table 1 and 2). The second step will involve switching to natural gas, with no additional equipment required except a connection to the available flare system at the North Campus. Several quick-closing valves will be used to isolate sections in case of an emergency or leakage in some part of the flow loop. The current flare system will be checked before switching to natural gas in terms of capacity, and flaring duration.

Experimental Setup

The facility is composed of gas, oil, water and separation systems and a test section. The operating pressure will be 500 psig. The flow loop length will be 523 ft, approximately. A schematic of the facility with all its components is shown in Fig. 1A. Fig. 1B shows the layout and the space available for the flow loop. The test section will have the ability to be inclined 3^o upward and 3^o downward by switching the flow direction. Fig. 1C shows the location and details of the inclinable part. The natural slope of the ground will be taken into consideration, and elevations and the natural slope are shown in Fig. 1D.

The inclined section starts at a distance of 236 ft from the pipe inlet. The inclinable section length will be 287 ft, approximately. The L/D ratio at the beginning of the inclination part of the pipe will be around 472. The test section of the inclined part of the pipe will be 140 ft from the pipe outlet, which makes the L/D ratio on the inclinable section only (from starting point of the inclined section to the test section) around 280 to ensure a fully developed flow.

The support system will be constructed on pillars support made of I-beams as shown in Fig. 1E. Supported beam details are given in Fig. 1F.

Operating Conditions Range

Flow pattern maps have been generated using the Barnea model (1987) with two water cuts (0 % and 100%) for a 6-in diamter pipe at 500 psig system operating pressure as shown in Fig. 2. The operating range of the facility can be decided based on the flow pattern maps.

The maximum superficial gas velocity will be 10 m/s at 500 psig. The maximum superficial liquid velocity will be 0.7 m/s with water cut from 0 to 100%. With these superficial velocities, Fig. 2 shows that the flow patterns will be mainly stratified and intermittent.

Gas, Oil, Water and Separation Systems

According to the maximum gas and liquid superficial velocities, the capacities of the compressor, pumps, separator, heat exchanger, chiller and tanks can be decided. For the compressor, the design flow rate, discharge and suction pressures are 18 MMSCFD, 500 psig and 400 psig, respectively. For the pumps, the design flow rate is 200 GPM with the same discharge and suction pressures as the compressor. The volume of the oil tank and water tank should be 1200 gallons and have pressure rating of 600 psig. The dimensions of the cylindrical three-phase separator will be 54" x 10'. The separator will have a pressure rating of 600 psig.

Heat Exchanger & Chiller

Based on the Sundyne compressor specification sheet for inlet conditions of 414 psia and 100 F, the outlet condition will be 515.7 psia and the outlet temperature will be 138.2 °F. There will be an increase in temperature of about 38 °F. A heat exchanger is needed to reduce the gas temperature from 138.2 °F to the inlet temperature (100 °F). Based on all parameters summarized in Table 3 for natural gas (Methane), a heat exchanger with a maximum (at maximum flow rate) heat duty of 210 KW (720,000 BTU/HR) is required. Chilled water must be provided to the heat exchanger. Based on the maximum operating condition, a 60-ton chiller must be used. For Nitrogen as the gas phase, a heat exchanger with a heat duty of 298 kW (1,017,723 BTU/HR) is required and a chiller with 85 ton capacity is needed to provide the chilled water to the heat exchanger at maximum flow rate.

Test section

The inner diameter of thr test section will be 6 in. A proposed design of the test section is shown in Fig. 1B. With this design, the flow developing section will be longer than the exiting test section. The inclination angle can be changed from -3 to 3 degree by changing the inlet. Two measurement sections will be made. The first one at 135 ft and the second at 440 ft from the entrance corresponding to L/D values of 270 and 880, respectively. To minimize the effect of pipe bend, a very long bend with 15-ft radius will be installed.

Basic Instrumentation

The following are proposed instrumentation for the high-pressure flow loop.

Pressure and temperature

Flow rates for gas, oil and water phases will be measured by Micro Motion flow meters. Pressure and temperature will be measured by pressure and temperature transducers, respectively. Differential pressure transducers will be mounted on the test section and developing section to measure the pressure gradient and to monitor the flow development. These instruments will be high pressure rated.

Liquid holdup

Total liquid holdup

Quick closing valves will be used to measure the total liquid holdup. A trapped liquid measurement vessel shown in Fig.3A needs to be designed to measure the volume of the trapped liquid for two-phase flow (gas and water). In addition, the liquid level in the pipe will be measured through the viewing window. For three-phase flow of water, oil and gas, especially at low water cut, some of the residual oil may remain in the pipe. This will be checked using a Gamma Ray Densitometer and viewing port. An uncertainty analysis will be performed to determine the amount of residual oil statistically. In addition, a measurement of the height of the liquid level and the wetted pipe perimeter will be used to calculate the total liquid holdup in some cases (high and low water cuts). Different view port designs will be discussed later.

Oil and water holdup

Oil and water holdup measurements will be one of the most difficult tasks. Using the scale on the view port may not give the oil or water holdups separately since the distribution of oil and water (at certain water cuts) may not be two segregated liquid layers on top of each other. If the two liquid phases were completely segregated, we can use the height measurement to calculate the liquid holdup. A new technique will also be developed to measure the height of the water and oil based on two laser sensors, one from the top and another from the bottom, in case of the segregation. This technique will be developed and tested in house. The height of the water film will also be measured by the conductance probe technique. It is worth mentioning that to low pressure experiments we have used a pigging system to push all the liquid out of the trapped space between the two quick-closing valves (especially at low water cut) which is not possible in the high pressure case. High pressure may be used to flush the liquids out to an external lower pressure vessel. Then, we can use any separation technique to get phase fractions. After flushing all the liquid out of the trapped space between the two quick-closing valves, a densitometer will be used to scan the area between the quick closing valves to make sure there are no residual liquids left. An uncertainty analysis will be conducted to evaluate any oil residual. In some cases, a Gamma-Ray densitometer may give the holdup measurement. All available and applicable techniques will be implemented and compared to achieve accurate measurements.

Another procedure that can be used was suggested by Yongqian Fan of Conoco Phillips and is depicted in Fig. 3B. It utilizes a collecting container (500 psi rated) and a Micro-Motion flow meter. The collecting container is actually a small 2-phase separator, which consists of a cylinder, an inlet (connected to drainage pipe from test section), a gas outlet at the top (connected to the 3-phase separator), and a liquid outlet at the bottom (connected to a Micro-Motion flow meter, then merges with the pipe from the gas outlet to the 3-phase separator). One more pipe is needed to connect the high pressure gas to the part between the quick-closing valves. This helps drain liquid from the test section to the collecting container, and also pushes liquid from the collecting container through the Micro-Motion flow meter to the 3-phase separator.

Film thickness

The film thickness of the water will be measured using a conductivity probe. The total film thickness will be measured visually by measuring the height of liquid using a scale pasted on the viewing port. The accuracy of this measurement will depend on the interface shape between the liquid and the gas.

Film thickness and wetted perimeter can also be estimated using a Gamma Ray Densitometer.

Liquid velocity

The liquid velocity will be measured by injecting a cold liquid at the same or slightly higher pressure. The injected cold water will be supplied by a pump or a pressurized tank, as shown in Fig. 4. The difference in temperature along a certain distance over a period of time will be used to calculate the liquid velocity. The time difference between the temperature peaks detected by two temperature probes will be recorded with a high-speed data acquisition system.

Liquid Entrainment

Liquid entrainment will be measured by using an Iso-kinetic probe with high pressure rating, as shown in Fig. 5. The stagnation probe, separator, and container will be high pressure rated. The gas outlet will be connected to the flow loop separator, which is the lowest pressure point in the system. The challenges in this technique are the probe tube seal into the pipeline which must be perfect, and the high-pressure rating of the other components.

Flow pattern

The visual observation of the flow pattern will be done through a viewing port or/and through a video Borescope with a built in lightning system. The commercial viewing ports or sight indicator available in the market are not made with careful attention to flow pattern. The available sight indicators usually disturb the flow pattern, either by the expansion of the inside diameter right at the viewing window or by the flat glass (sapphire or acrylic) piece on a round pipeline surface.

Different designs for the viewing port are considered and presented below:

Design A: Whole perimeter viewing section

This design is made of a thick piece of polycarbonate acrylic that covers the whole parameter of the pipe as shown in Fig. 6. The thick piece of acrylic will be fixed by two flanges. A destructive test will be performed to make sure that this design will handle more than 500 psig.

Design B: Partial perimeter viewing section

This design is based on a sight indicator available in the market with some modification to remove all the flow disturbance sources from their design (Fig. 7). It consists of two pieces of polycarbonate acrylic inserted inside a containing flange. The inserted acrylic piece will have the same curvature as the inside pipe diameter, so it will not cause any flow disturbance.

More instrumentation will be implemented depending on the needs of the research project.

Feed back and Comments of TUFFP Members

Safety Issues

Several feedbacks from TUFFP members have been received concerning the safety requirements of the facility. The challenges are mainly coming from the location and space available and if the loop will have enough distance from the nearest office trailer, machine shope and residential area. A residential area is located on the east and north sides of the pipeline next to the wooden fence (the pipeline is 15-ft away from the fence). The University machine shop is located on the south side of the pipe line area (the pipeline is 20 ft away from the machine shop). The onsite control room at the center of the loop area is shown in Fig. 1B. Finding the right safety regulations that fit our case is another challenge.

Considering the safety issues

In considering the safety concerns we have first suggested using Nitrogen as a transition stage in our studies. The objectives of the transition studies are;

- To master/ control all sections at high pressure for issues of seal and instrumentation connections using less hazardous gas
- .To train our staff and students and establish a procedure for using the high pressure facility
- To obtain data at higher gas density, especially for entrainment for comparison purposes.

Secondly, for the final stage of this project, we will use natural gas as the gas phase with the following precautions:

- A line from the flow loop to the existing flare system needs to be installed. The natural gas pressure will be reduced by passing it to a tank (this tank will be located close to the existing flare system). Then, the new reduced pressure will be bleed to the low flaring pressure by using two needle valves and a pressure regulator.
- Several emergency quick-closing valves will be installed by which the flow loop can be separated into sections incase of any leakages.
- The electrical power generator will be installed away from the flow loop, eliminating any source of ignition.
- A restrict running and training procedure will be established for the safety of the operator and the facility.

Solubility Issues

A concern has been raised about whether the Nitrogen will have similar behavior as the methane because of the lower solubility of the Nitrogen compared to Natural gas. The solubility of natural gas is about 4 times that of Nitrogen on a mole basis and is about twice on a mass basis due to the differences in their molecular weights. The solubility will mainly affect the viscosity of the flowing liquid, but at the end the flow behavior will be almost comparable. Regarding the entrainment fraction, the main factor is the difference in the gas density at the operating pressure, which will be recorded.

Temperature Control

A suggestion for insulating the pipe for better temperature control has been given. This suggestion will be considered and the pipe will be insulated.

Pipe Material

Some of the fluids used will be corrosive. Previously carbon steel was the material of the pipe, but now we are considering Stainless steel. The price of the stainless steel is about 3 times higher than the carbon steel and the machining cost is also higher. However, the pipe cost is not a major cost of the project investment and switching to Stainless is a good idea and will be considered.

Separation System

Using a gas liquid separator followed by a lower pressure liquid-liquid separator in case of running high viscosity oil has been suggested. The flow loop components have been designed for low viscosity. However, in case of running high viscosity liquid a parallel separating system and pumps have to be installed.

Other suggestions

We should consider using liquid sampling Vs. monitoring of water in oil or oil in water techniques and conduct training to operate the loop safely plans far in advance. These two suggestions are considered. We will be able to get samples from the liquid between two quick closing valves and also we will be having training procedure for all personnel.

Near Future Plan

An effort has been made to get an external consultant opinion concerning the safety and operability issues. The following steps have been achieved after several attempts:

- The local fire marshall was contacted to obtain the appropriate rules and regulation, and permitting process.

- Enserca Engineering is the engineering company that has agreed to work with us through the permitting and design stage of the project, Additive Systems Inc. will handle significant portion of the construction.

Capital investment

The design and construction of a high pressure and large diameter facility is a very significant capital investment for TUFFP. All the equipment items will be purchased or a bid basis and negotiated with suppliers. The estimated costs for the three phase facilities are listed in Table 3. Labor cost is not included.

Time Table

The completion of the design and construction of the facility is expected by March 2009 (see Table 4). The most time consuming item is the Compressor. Once the compressor is ordered, it takes about 6-8 months to receive the delivery. Purchase order of the compressor has been already placed.

Proposed Initial Project

Investigation of low liquid loading at high pressures is proposed to be investigated as the first research project for this facility.

References

Barnea, D.: "Unified Model for Predicting Flow-Pattern Transitions for the Whole Range of Pipe Inclinations," *Int. J. Multiphase Flow* (1987), **11**, 1-12.

Table 1: Natural gas properties and flow conditions for Heat Exchanger design

Natural gas properties	**English Units**	**SI Units**
Outlet Temperature , T	100 F	311 K
Intlet Temperature , T	138 F	332 K
Pressure, p	500 psig	3447.379 KPa
gas constant, R	0.1238 BTU/lbm-R	0.5182 kJ/Kg-K
critical point temperatue, Tc	343.9 R	191.1 K
critical point pressure, Pc	673 psia	4.64 MPa
Compressibility factor, Z	0.95	0.95
Flow density	1.448329 Lb/Ft^3	23.2 Kg/m^3
Mass flow rate at v_{SG} =10 m/s	9.325543 lb/s	4.23 Kg/s
Specific heat of at 300 K, Cp	0.532 BTU/lbm-R	2.2537 KJ/Kg-K
Heat Exchanger heat duty per pass	720,000 BTU/HR	210 KW
Chiller capacity	**60 ton**	

Table 2: Nitrogen properties and flow conditions for Heat Exchanger design

Nitrogen properties	English Units	SI Units
Outlet Temperature , T	132.6 F	329 K
Intlet Temperature , T	60 F	288 K
Pressure, p	500 psig	3447.379 KPa
critical point temperatue, Tc	227.16 R	126.2 K
gas constant, R	0.0709 BTU/lbm-R	0.2968 kJ/Kg-K
critical point pressure, Pc	491.67 psia	3.39 MPa
Compressibility factor, Z	1	1
Flow density	2.4 Lb/Ft^3	38.5 Kg/m^3
Mass flow rate at v_{SG} =10 m/s	15.43 lb/s	7 Kg/s
Specific heat of at 80 F, Cp	0.248 BTU/lbm-R	1.039 KJ/Kg-K
Heat Exchanger heat duty per pass	1017723 BTU/HR	298 KW
Chiller capacity	85 ton	85 ton

Table 3. Facility Capital Cost Analysis (in $1000)

	Component	Capacity	Cost	Status
1	**Compressor**	18 MMSCFD	242	O.P.
2	**Compressor surge control**	Dual loop controller	25	Q.R.
3	**Heat Exchanger**	1017723 BTU/HR/pass	18	Q. R.
4	**Chiller**	90 ton	60	Q. R.
5	**Safety Valves**	2	2	
6	**Water Pump**	200 GPM	20	Q.U.
7	**Oil Pump**	200 GPM	20	Q.U.
8	**Separator**	54" x 10' @ 600 psig	36	Q. R.
9	**Water Tank**	1200 gallon	33	Q. R.
10	**Oil Tank**	1200 gallon	33	Q. R.
11	**Gas Flow Metering**	18 MMSCFD	20	
12	**Water Flow Metering**	200 GPM	20	
13	**Oil Flow Metering**	200 GPM	20	
14	**Differential Pressure**	(8) with proper range	8	
15	**Pressure**	(8) with proper range	5	
16	**Temperature**	0-100 °C (8)	5	
17	**QCV**	6 in ID (7)	12	
18	**Power Generator**	500 KW	65	Received
19	**Steel structure &Tilting**		50	
20	**Stainless steel pipe**	Schedule 40 304 SS	90	
21	**Pressure Regulator**	3 (oil, water & gas)	5	
22	**Concrete foundations and pillars**	600 ft by 5 ft	50	Q.U.
23				
	Total		**$ 840K**	

Q. R.: Qoute Received ; Q. U.: Qoute Underway; O.P.: Order Placed

Table 4: Time Table for Facility Construction

Tasks	Status	Completing Time/ or required time
Quotation & order	Under way	June 30, 2008
Engineering design, review		8-10 weeks
Equipment manufacture		
Compressor	O.P.	28 -30 weeks
Pump	Q. U.	13 weeks
Heat Exchanger	Q. R.	15 weeks
Chiller	Q. R.	15 weeks
Separator	Q. R.	20 weeks
Tank	Q. R.	15 weeks
Power generator	Received	
Construction		August 30, 2008
Calibration & shake down tests		Feb. 30, 2009

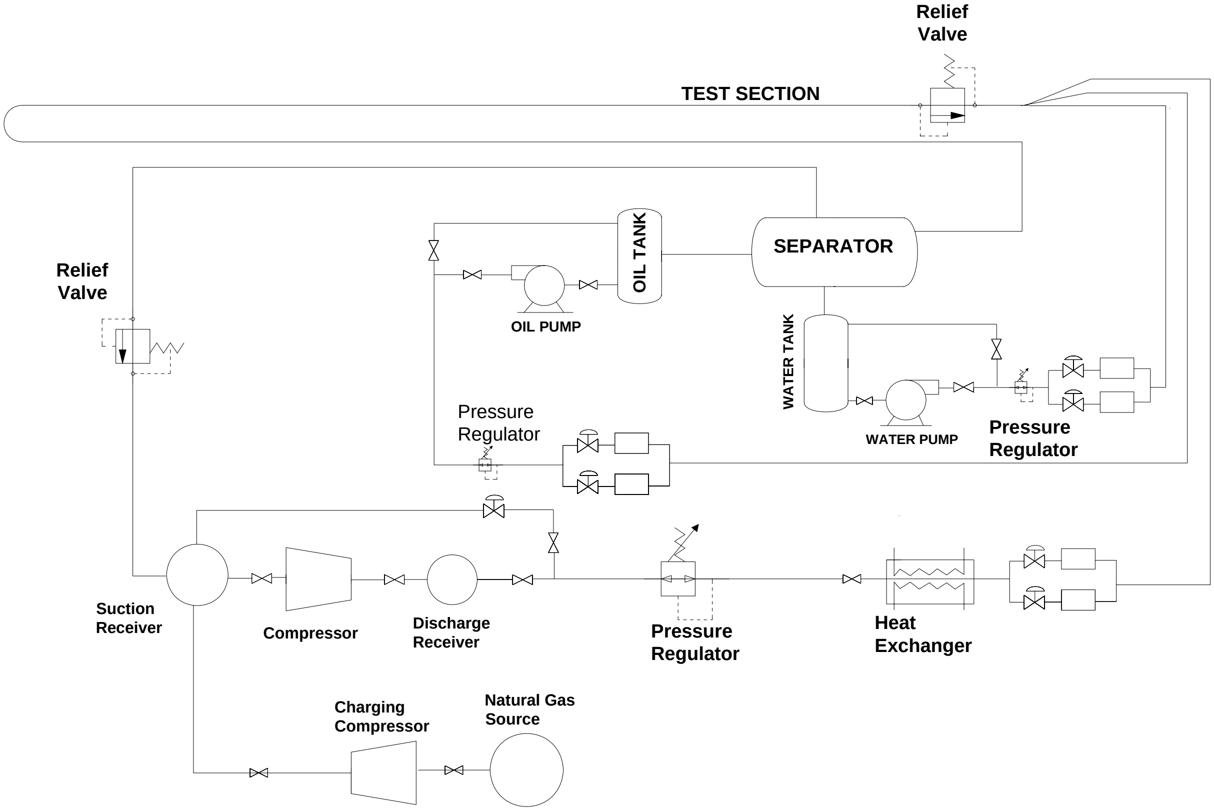


Figure 1A. Schematic of high pressure facility

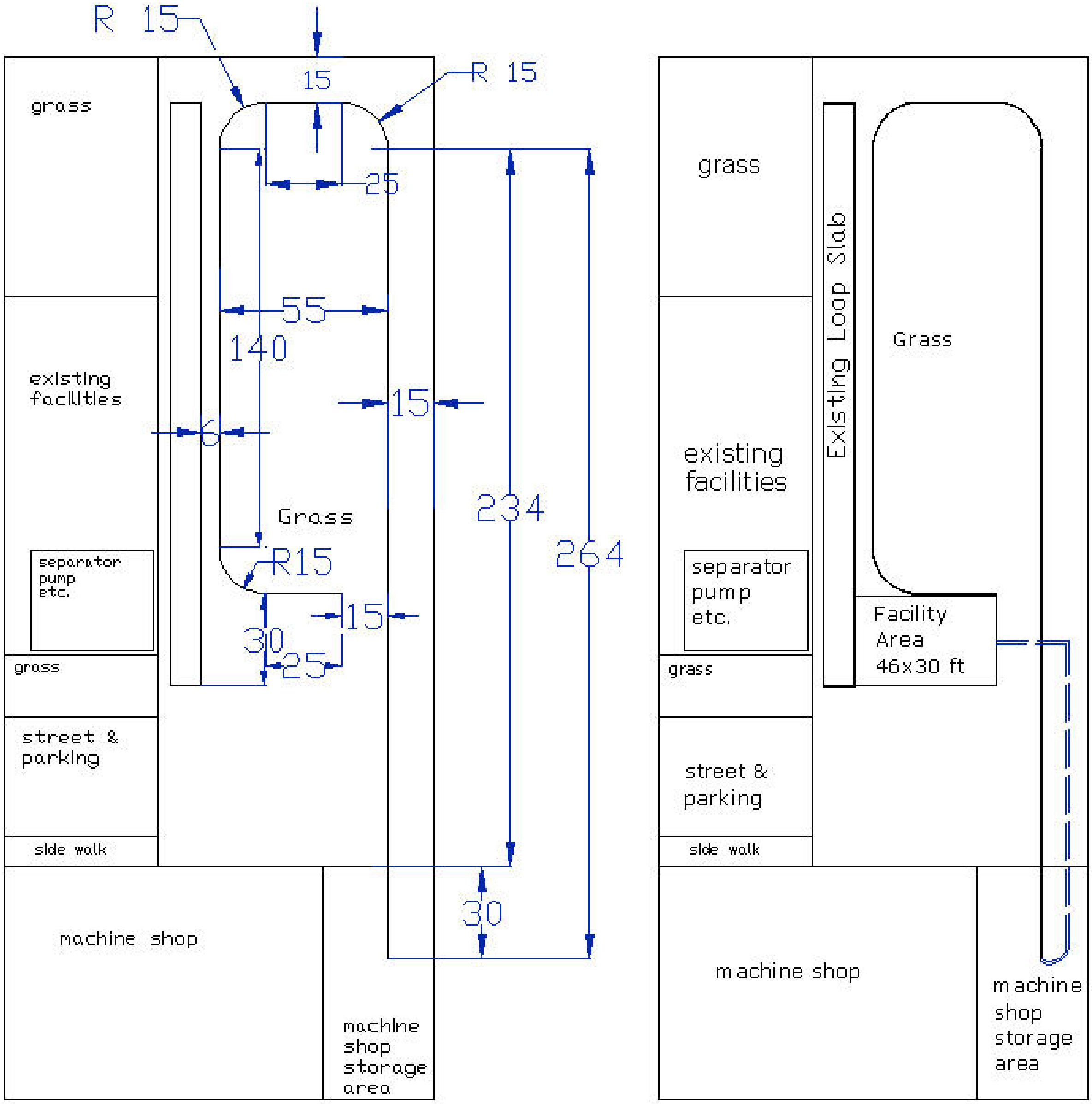


Figure 1B: Flow loop layout and the available space (dimensions are in feet)

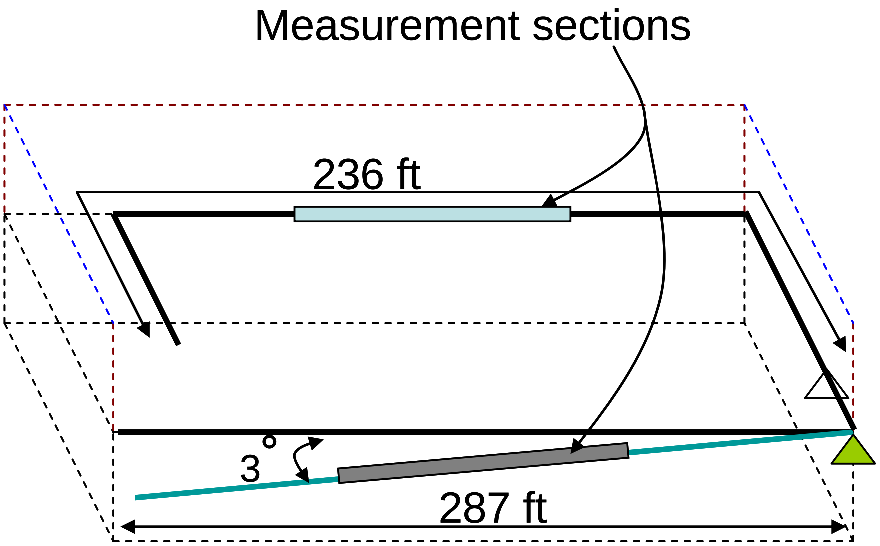


Figure 1C: Pipe inclination details

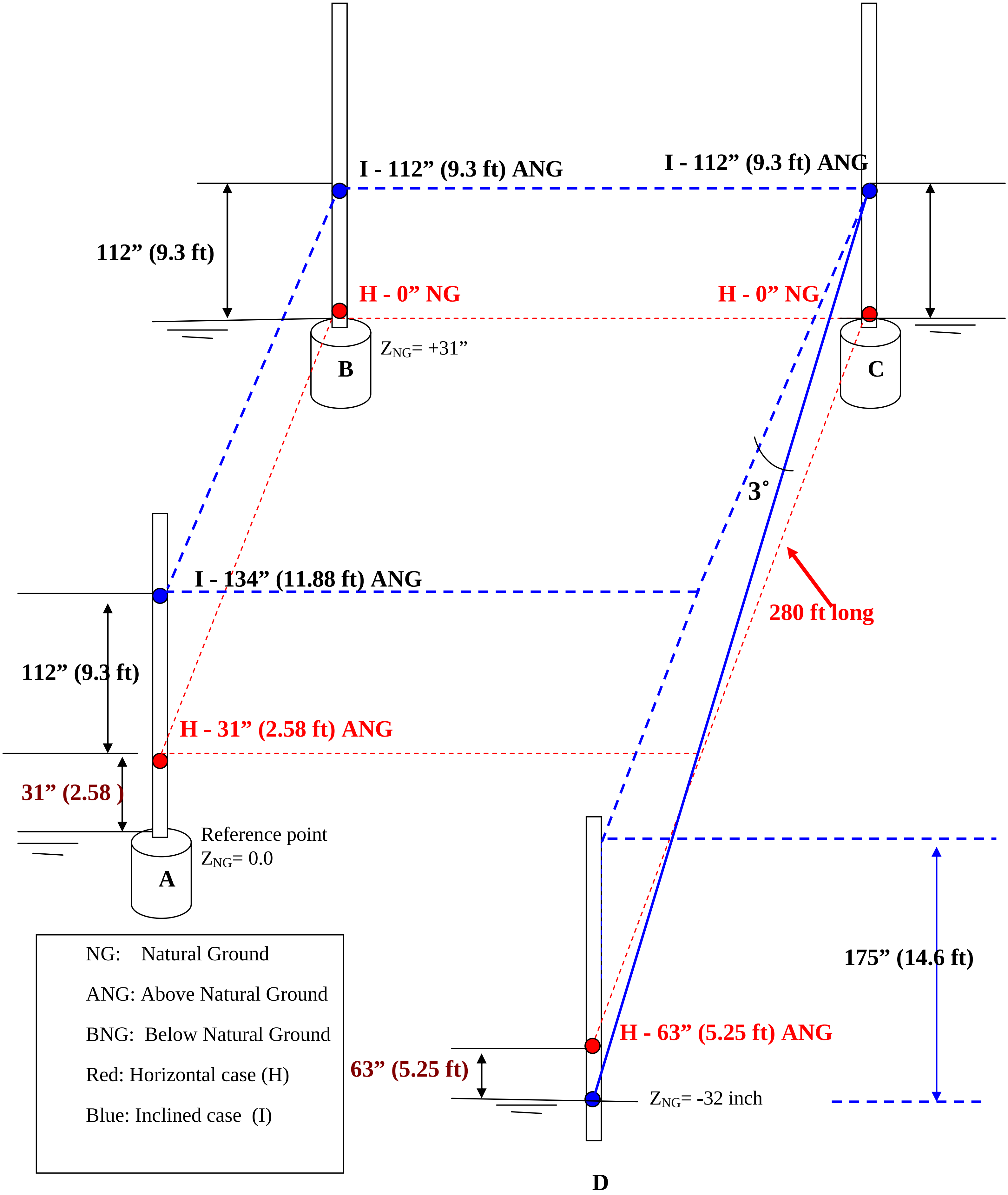


Figure 1D: Loop elevations and Natural ground slope

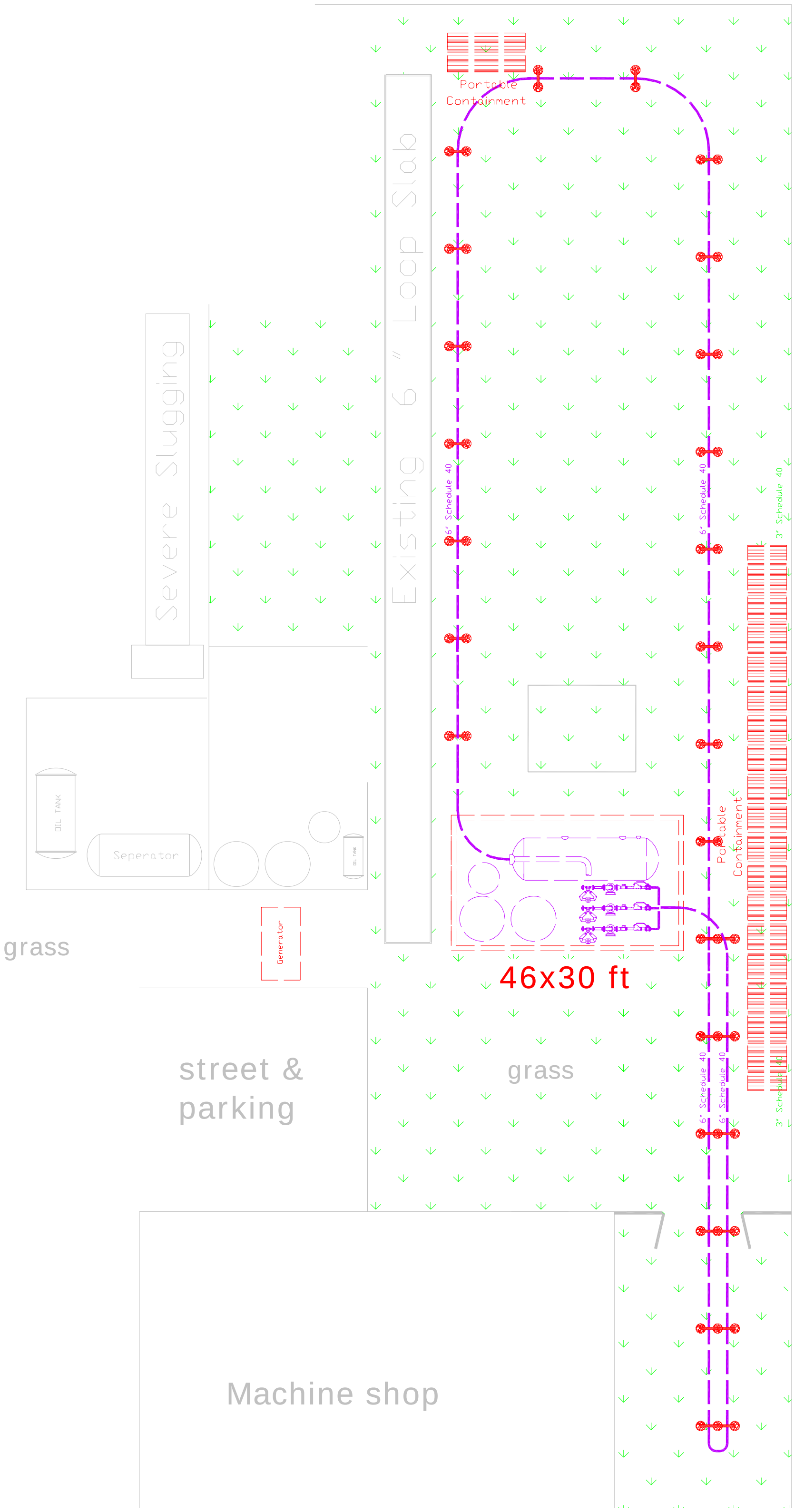


Figure 1E: Pillar system and supported beams

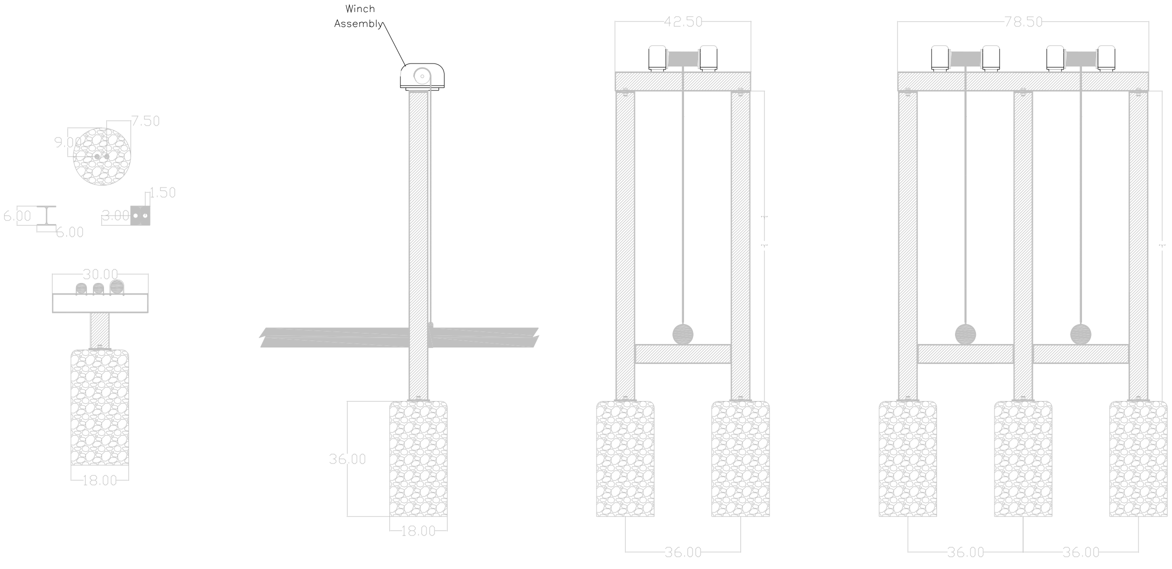


Figure 1F: Supported beam details (dimensions are in inches)

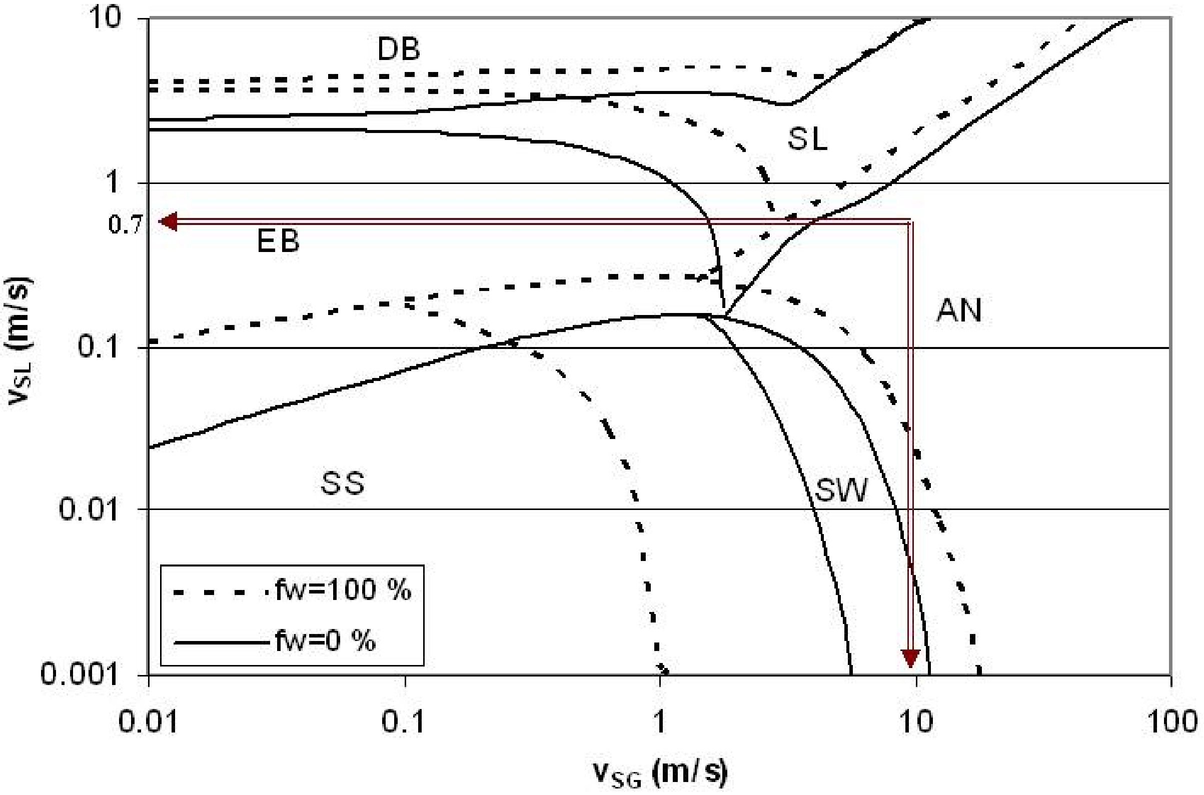


Figure 2. Flow pattern map for 100% and 0% water cut at 500 psig, 6 in. pipe

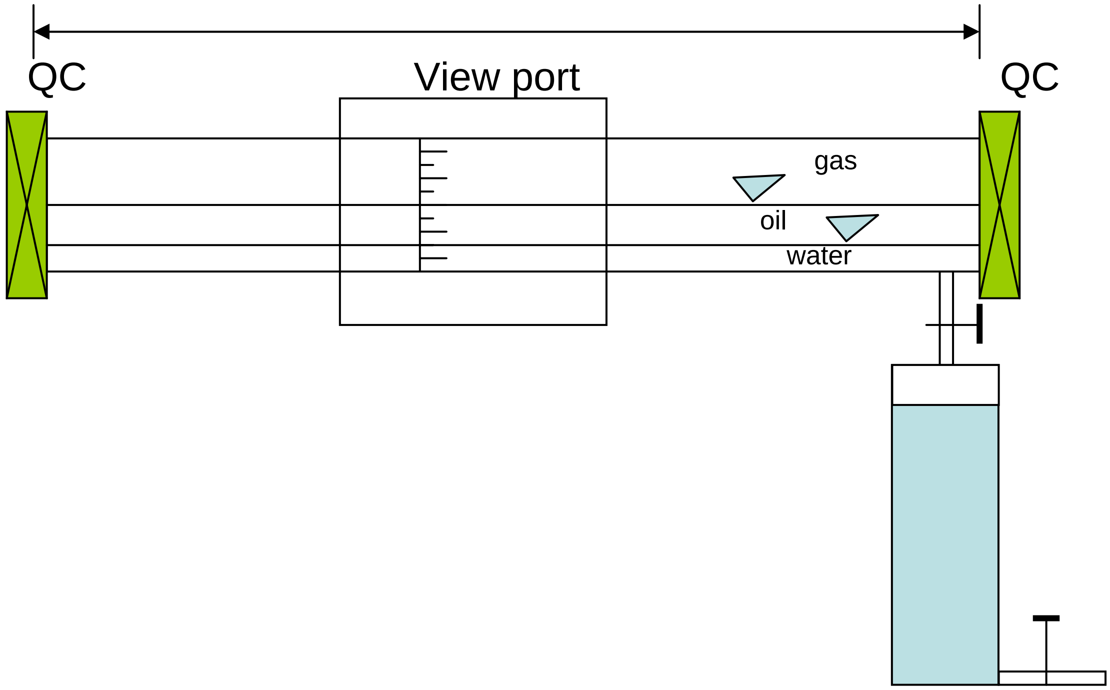


Figure 3A: Liquid hold up measurement technique

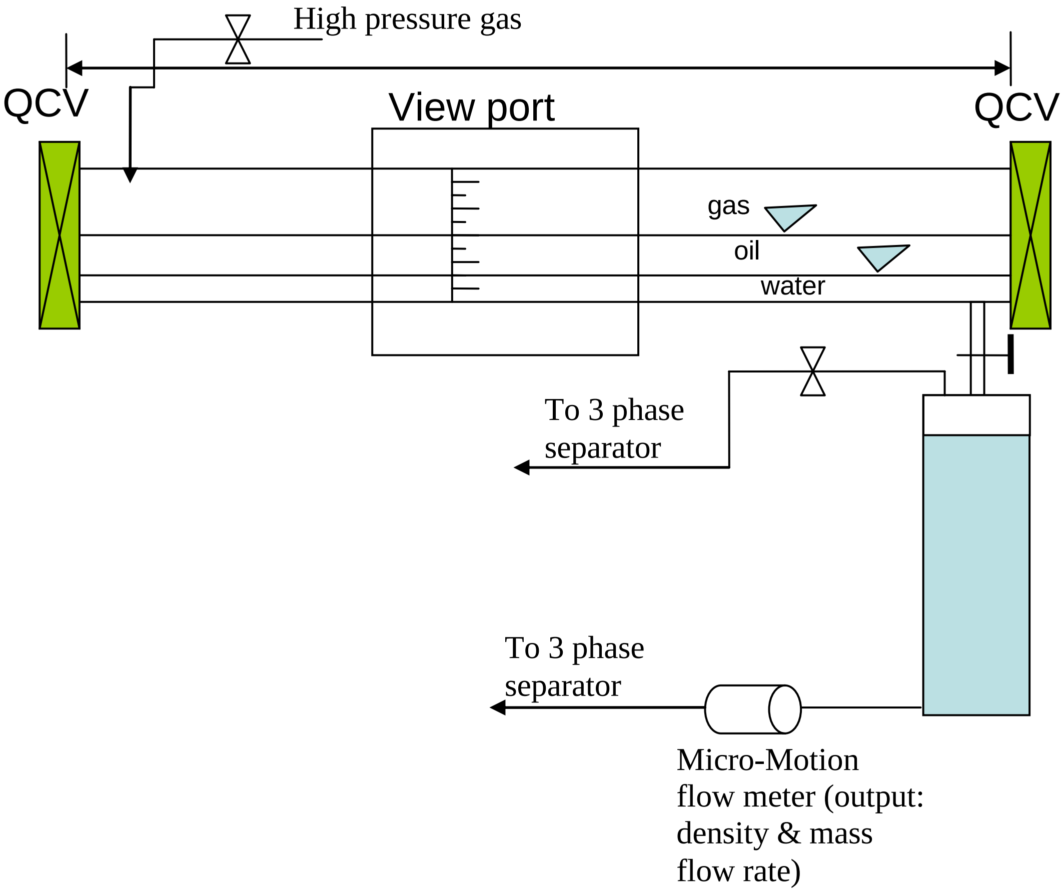


Figure 3B: Liquid hold up measurement technique (Yongqian Fan suggestion)

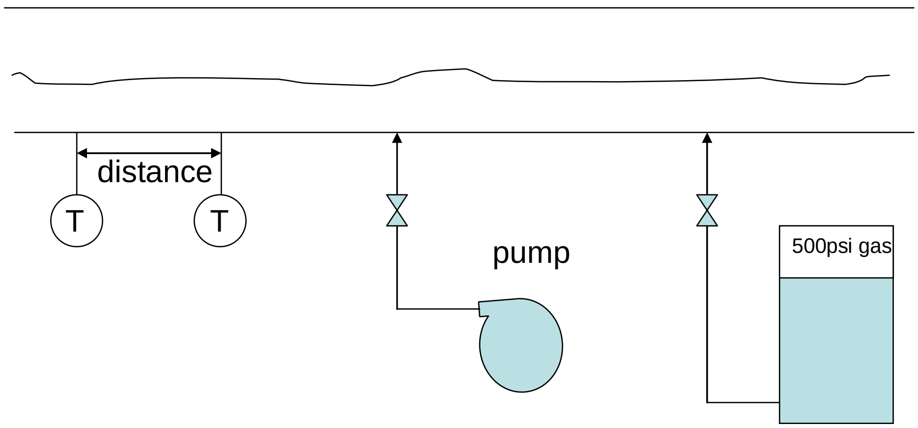


Figure 4: Liquid film velocity method

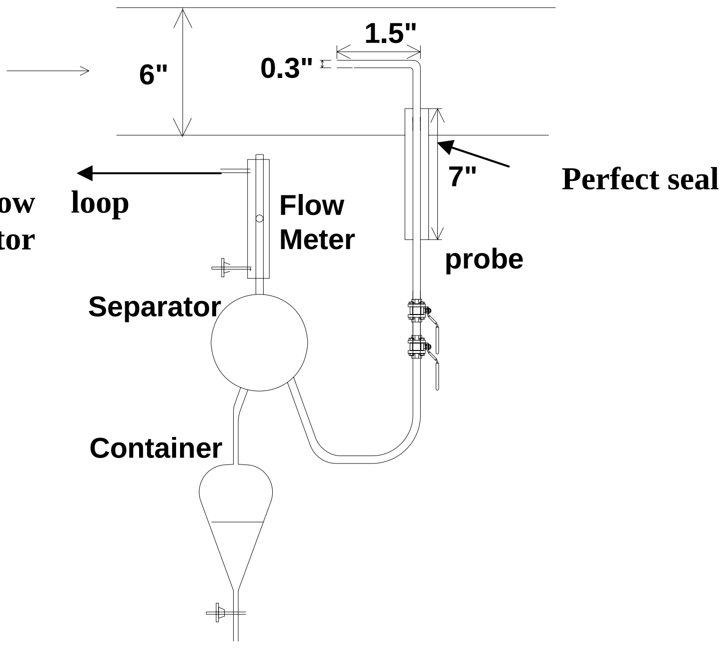


Figure 5: Iso-kinetic probe - high pressure rating

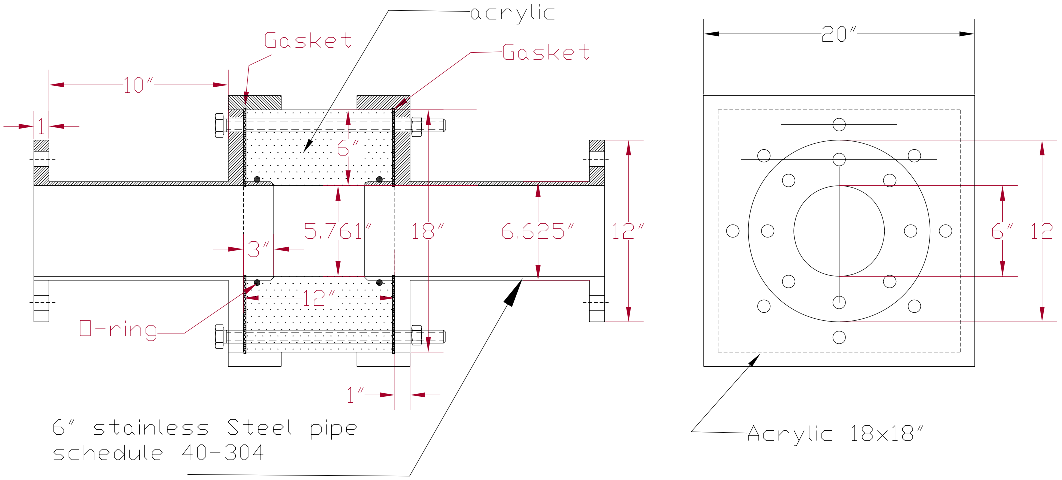
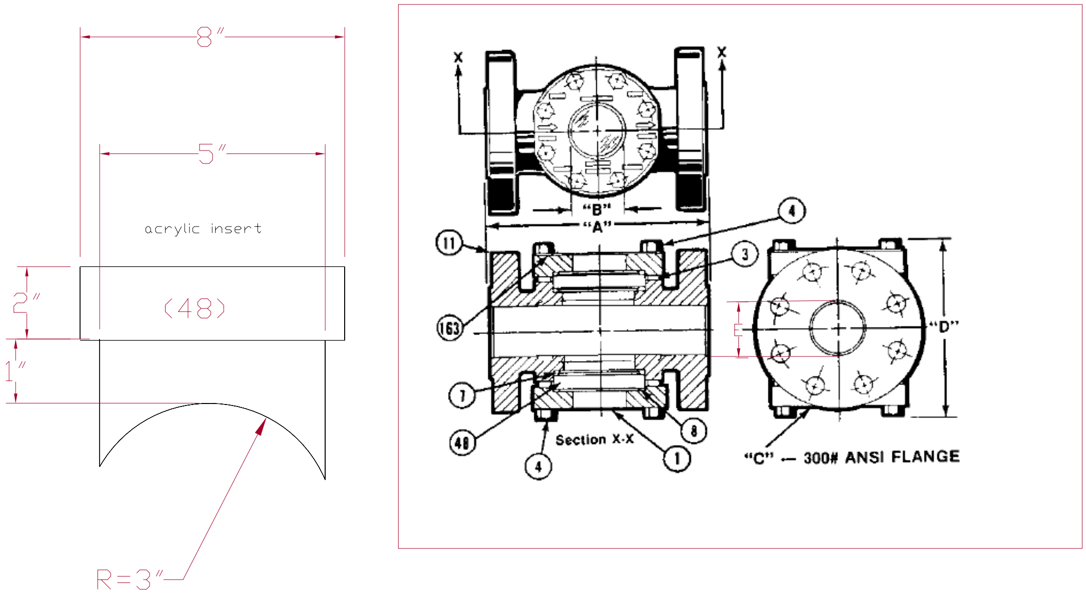


Figure 6: Viewing port (*Design A: Whole perimeter viewing section)*



A: 21 inch
B: 6 inch
C: 17 inch
D: 17 inch
E: 6 inch
the inner pipe diamter is 6 inch
ANSI class 300# flange will allow
up to 500 psig

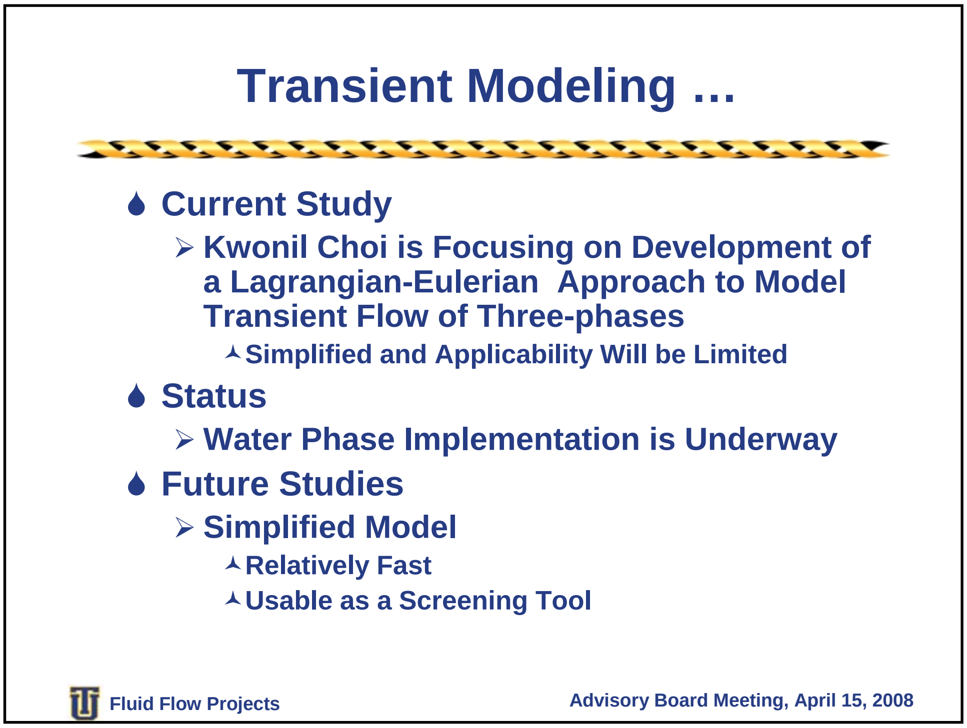
Figure 7: Viewing port *(Design B: Partial perimeter viewing section)*

Transient Modeling

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

Transient Modeling …

- Objective
  - Development and Testing of a Simple Transient Flow Simulator
- Past Studies
  - TUFFP has Conducted Many Transient Multiphase Studies
    - Scoggins, Sharma, Dutta-Roy, Taitel, Vierkandt, Sarica, Vigneron, Minami, Gokdemir, Zhang, Tengesdal, and Beltran



Transient Modeling …

- Current Study
  - Kwonil Choi is Focusing on Development of a Lagrangian-Eulerian Approach to Model Transient Flow of Three-phases
    - Simplified and Applicability Will be Limited
- Status
  - Water Phase Implementation is Underway
- Future Studies
  - Simplified Model
    - Relatively Fast
    - Usable as a Screening Tool

Fluid Flow Projects

Lagrangian-Eulerian Transient Two-Phase Flow Model

KWON IL CHOI

Advisory Board Meeting, April 15, 2008

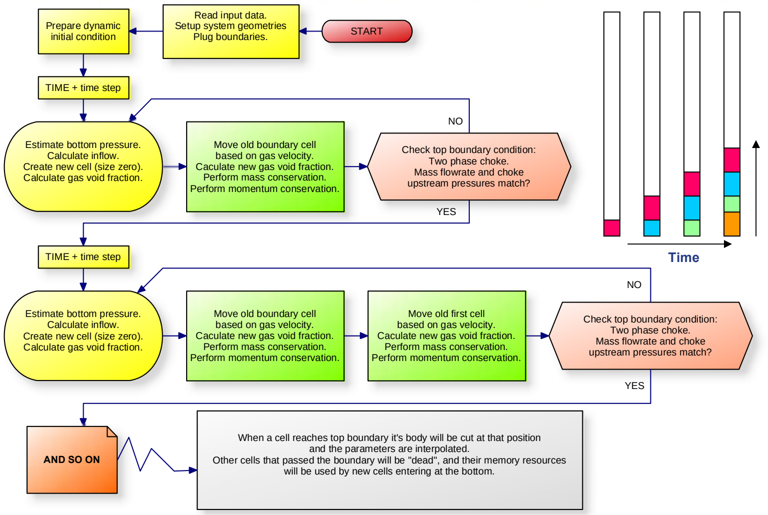
Outline

- Objectives
- Computational Model
- Problems in the Current Model
- Possible New Approaches
- Project Schedule

Objectives

- Computational Modeling of Transient Two-phase Flow Coupled with TUFFP Unified Mechanistic Model
- Model Validation through Experiments
  - Severe Slugging
  - Shut-in
  - Gas Lift

Computational Methodology



START

Read input data.
Setup system geometries
Plug boundaries.

Prepare dynamic initial condition

TIME + time step

Estimate bottom pressure.
Calculate inflow.
Create new cell (size zero).
Calculate gas void fraction.

Move old boundary cell based on gas velocity.
Caculate new gas void fraction.
Perform mass conservation.
Perform momentum conservation.

Check top boundary condition:
Two phase choke.
Mass flowrate and choke upstream pressures match?

TIME + time step

Estimate bottom pressure.
Calculate inflow.
Create new cell (size zero).
Calculate gas void fraction.

Move old boundary cell based on gas velocity.
Caculate new gas void fraction.
Perform mass conservation.
Perform momentum conservation.

Move old first cell based on gas velocity.
Caculate new gas void fraction.
Perform mass conservation.
Perform momentum conservation.

Check top boundary condition:
Two phase choke.
Mass flowrate and choke upstream pressures match?

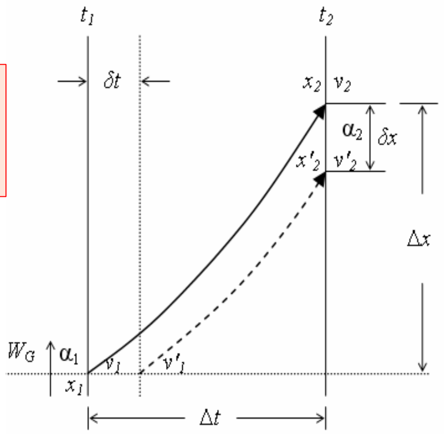
AND SO ON

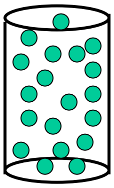
When a cell reaches top boundary it's body will be cut at that position and the parameters are interpolated.
Other cells that passed the boundary will be "dead", and their memory resources will be used by new cells entering at the bottom.

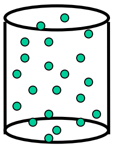
Lagrangian Gas Mass Balance

Gas Mass Balance

$$\alpha = \frac{m_G}{\bar{\rho}_G A_p \delta x}$$







Lagrangian Gas Mass Balance

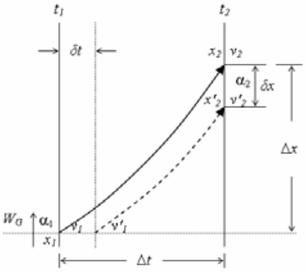
Gas Mass Balance

$$\alpha = \frac{m_G}{\bar{\rho}_G A_p \delta x}$$

$$m_G = \delta t \left(W_{G1} + \frac{1}{2} \frac{\partial W_G}{\partial t}\bigg|_{t_1} \delta t\right)$$

$$\bar{\rho}_G = \rho_{G2} + \frac{1}{2} \frac{\partial \rho_G}{\partial x}\bigg|_{x_2} \delta x$$

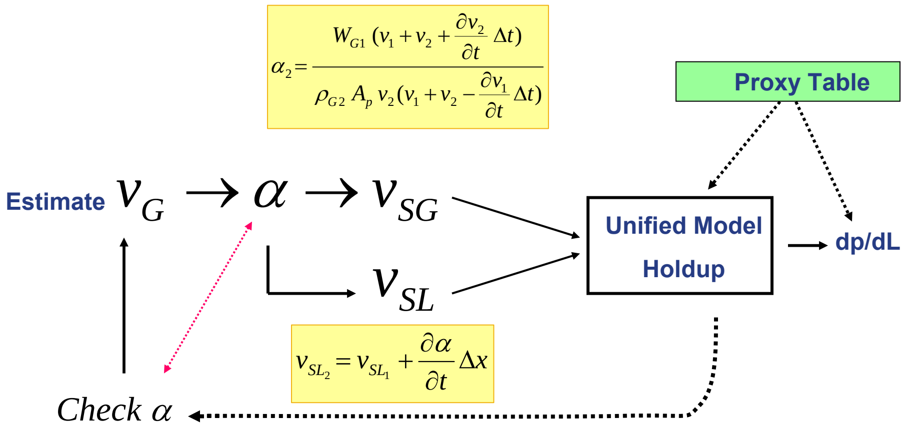
$$\delta x = \frac{(v_1 + v_2 - \frac{\partial v_1}{\partial t}(\Delta t - \delta t))\delta t}{2 - \frac{\partial v_2}{\partial x}(\Delta t - \delta t)}$$



$$\alpha_2 = \frac{W_{G1}\,(2 - \frac{\partial v_2}{\partial x}\Delta t)}{\rho_{G2}\,A_p\,(v_1 + v_2 - \frac{\partial v_1}{\partial t}\Delta t)}$$

Transient Modeling …

Coupling with Unified Steady State Model



$$\alpha_2 = \frac{W_{G1}\,(v_1 + v_2 + \frac{\partial v_2}{\partial t}\Delta t)}{\rho_{G2}\,A_p\,v_2 (v_1 + v_2 - \frac{\partial v_1}{\partial t}\Delta t)}$$

Proxy Table

Estimate $v_G \rightarrow \alpha \rightarrow v_{SG}$

v_{SL}

$$v_{SL_2} = v_{SL_1} + \frac{\partial \alpha}{\partial t}\Delta x$$

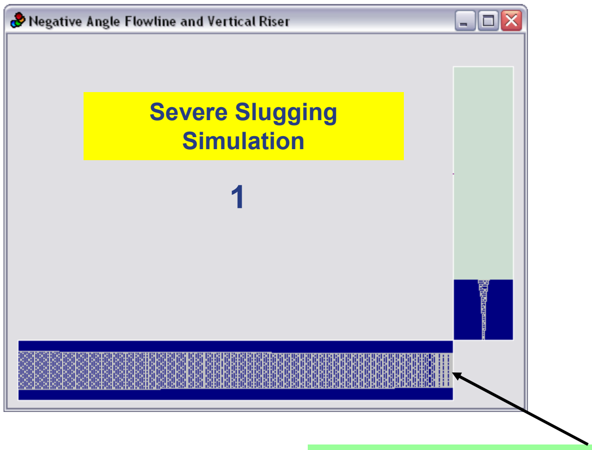
Unified Model

Holdup

dp/dL

Check α

Problem in the Model



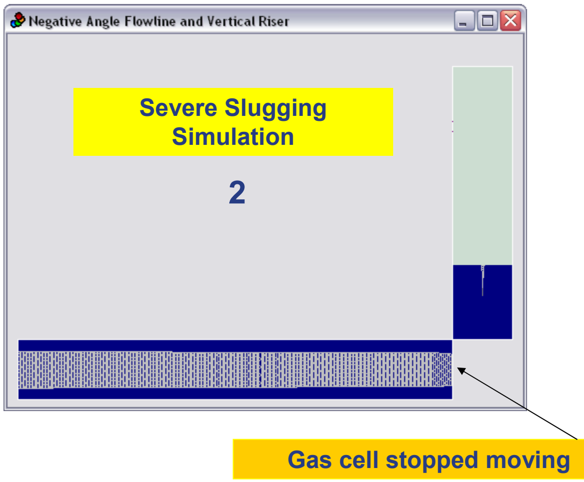
Negative Angle Flowline and Vertical Riser

Severe Slugging Simulation

1

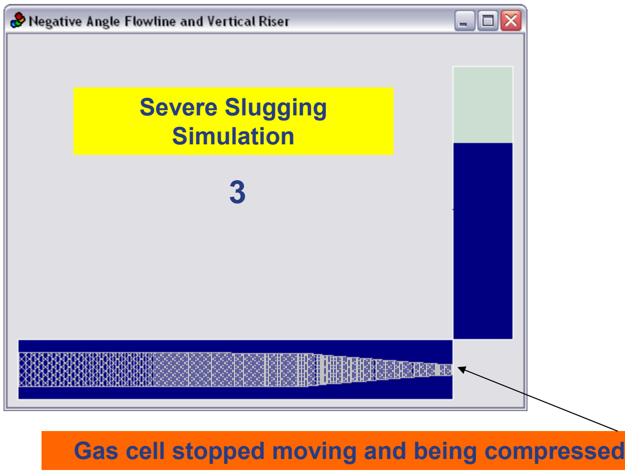
Gas cell moving forward

Problem in the Model …



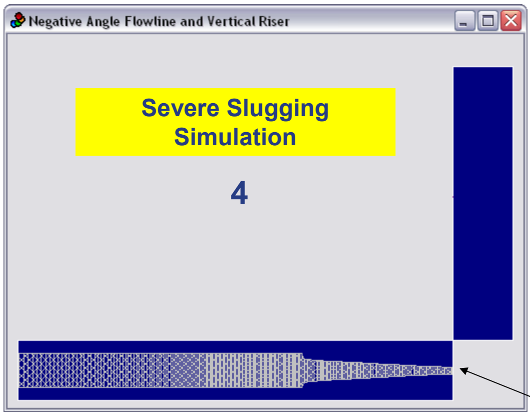
Gas cell stopped moving

Problem in the Model …



Gas cell stopped moving and being compressed

Problem in the Model …



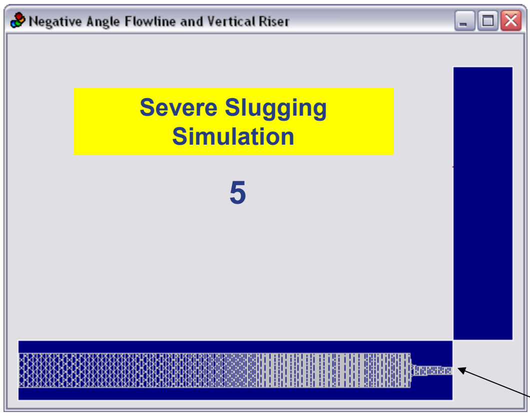
Negative Angle Flowline and Vertical Riser

Severe Slugging Simulation

4

Gas cell stopped moving. And being compressed

Problem in the Model …



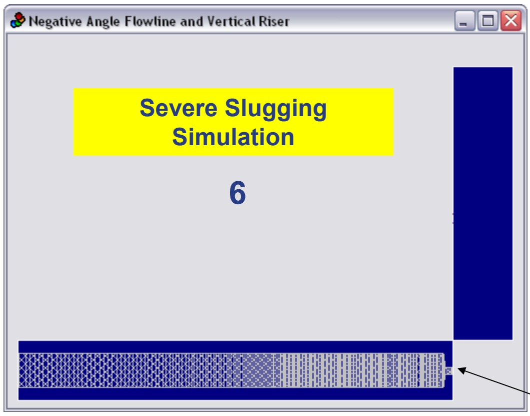
Negative Angle Flowline and Vertical Riser

Severe Slugging Simulation

5

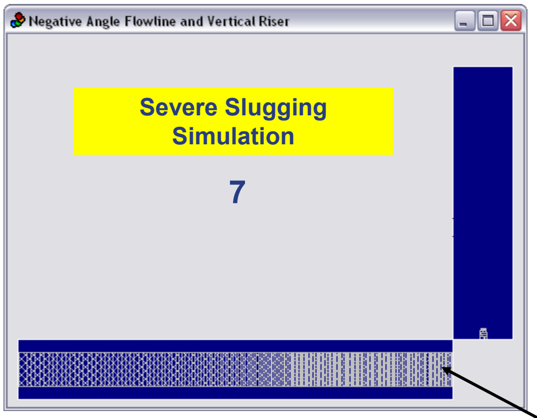
Gas cell not moving forward. Wrong !

Problem in the Model …



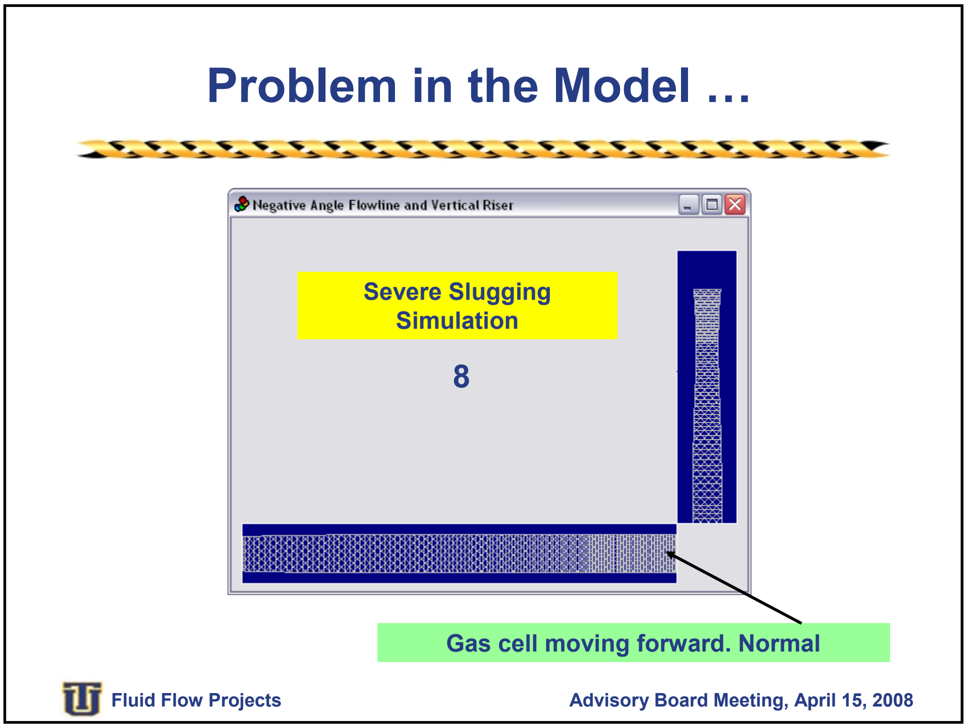
Gas cell being overridden by moving cells. Wrong!

Problem in the Model …



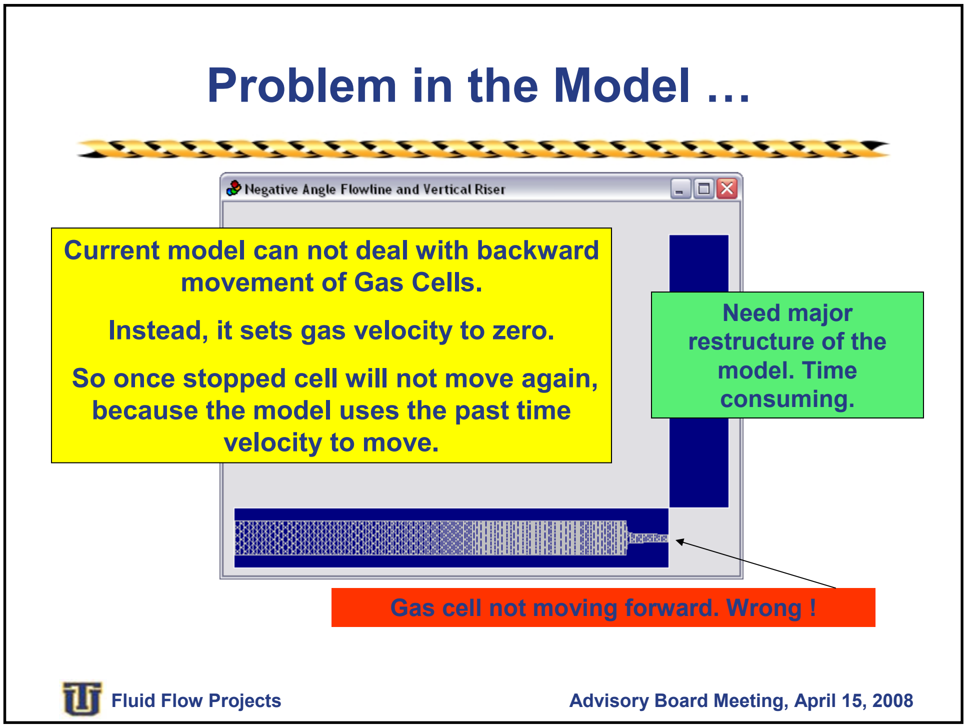
Gas cell moving forward

Problem in the Model …



Gas cell moving forward. Normal

Problem in the Model …



Current model can not deal with backward movement of Gas Cells.

Instead, it sets gas velocity to zero.

So once stopped cell will not move again, because the model uses the past time velocity to move.

Need major restructure of the model. Time consuming.

Gas cell not moving forward. Wrong !

Problem in the Model …

- Solutions:
  - Gas cell movement based on current updated velocity, implying one more level of iteration
  - Gas mass balance on the “cell body” instead of “cell boundary”
  - Artificially smooth transition between countercurrent and co-current backward flow

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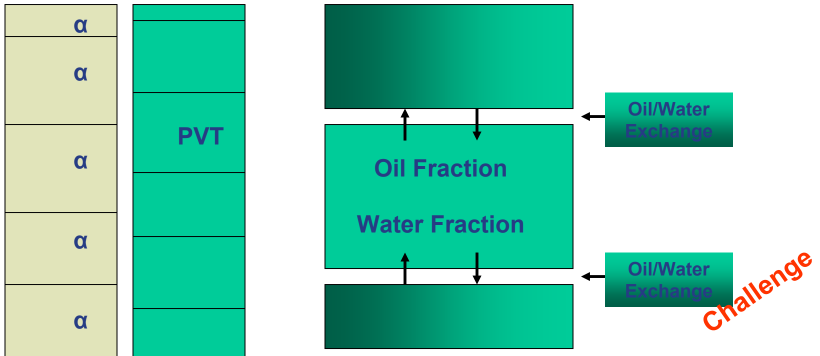
Oil-Water Segregation

Gas and Liquid Tracking Grids are Superposed

Oil-Water Segregation in Liquid Cells



PVT values are calculated on the boundaries (no volume)

Need volume information to update oil/water fraction in the cell

And, the liquid cell sizes are not 100% consistent.

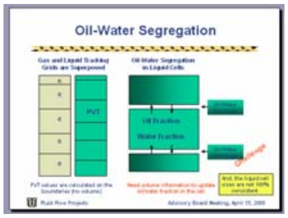
Oil-Water Segregation …

Solution:

- Liquid cell movement based on volume conservation instead of liquid in-situ velocity

Or

- Update water-oil fraction on the cell boundary instead of cell body



Oil-Water Segregation

Project Schedule

- PhD Research Proposal May 2008
- Model Validation with Existing Data September 2008
- Field Validation October 2008
- Final Report November 2008

Lagrangian-Eulerian Transient Two-Phase Flow Model

Kwon Il Choi

PROJECTED COMPLETION DATES:

Model Validation..October 2008
Final Report...November 2008

Objectives

The objectives of this study are:

- Computational modeling of transient two-phase flow coupled with TUFFP unified mechanistic model;
- Model validation through experiments.

Introduction

Description of the transient multiphase flow in the wellbore-flowline-riser system is one of the most complex problems in the petroleum production. A new approach for transient computational model for two-phase flow is introduced. In this model, gas mass tracking technique will be applied in order to get around the numeric diffusion which is a persisting problem for the transient multiphase flow programs based on Eulerian grid. TUFFP mechanistic Unified model can be coupled as a closure model for holdup calculation. Finally, quantitative experimental observations will be done to validate the theoretical model. Transient thermal calculations will be included in the model, but it can not be validated experimentally using the test facility.

Literature Review

Literature review will be an ongoing effort. During this period a search has been done for applications of Lagrangian-Eulerian fluid dynamics in multiphase pipe flow in petroleum engineering, without success. Computational approaches using Lagrangian-Eulerian method can be found in different areas like reservoir engineering, chemical engineering and astrophysics. One example of Lagrangian remapping scheme being applied for solving the nonlinear fluid equations in astrophysics is given by Lufkin *et al.*(2001). The common goal is "using Lagrangian numerical methods to avoid problems associated with numerical smearing in Eulerian calculations" (Lufkin and Fawley (1993)).

Computational Methodology

The Lagrangian transient multi-phase flow model, based on moving numerical grids, presents the important capability of better tracking the gas and liquid kinematics. This technique is not subjected to any numerical diffusion, which is the main drawback for the Eulerian models. At every time step, two moving grids, one for liquid and one for gas, are forced to move at different velocities, and then, they are frozen and superimposed to make material and momentum balances possible. The resulting finite difference cells become irregular and elastic for their sizes to change at each new time step.

Model Development

Modeling of Gas Mass Balance

A method to handle gas mass balance in a gas tracking numerical scheme is proposed. This is the key component of the model because it enables explicit calculation of gas void fraction in the moving node, and supports the liquid mass balance on the instantaneous remapped Eulerian grid.

In Fig. 1, the distance increases from bottom to top and the time increases from left to right. The schematic describes the movement of two different cross-sectional surfaces with conserved mass of gas contained between them.

If a known amount of gas (m_G) is contained within a small volume bounded by two cross-sectional surfaces at x_2 and x_2' with small length δx, then the local gas void fraction is given by

$$\alpha = \frac{m_G}{\overline{\rho}_G A_p \delta x}, \tag{1}$$

where $\overline{\rho}_G$ is the average gas density and A_p is the pipe cross-sectional area.

The amount of gas that passed the position x_1 during the small time interval δt is the same amount of gas contained in δx.

$$m_G = \int_{t_1}^{t_1+\delta t} W_G(t)\,dt\,. \tag{2}$$

The gas mass flow rate at x_1 is W_G and its change with time is represented by the truncated Taylor series around the time t_1.

$$W_G = W_{G1} + \left.\frac{\partial W_G}{\partial t}\right|_{t_1} (t - t_1)\,. \tag{3}$$

The integration in Eq. (2) results in the following equation

$$m_G = \delta t\,(W_{G1} + \frac{1}{2}\left.\frac{\partial W_G}{\partial t}\right|_{t_1} \delta t)\,. \tag{4}$$

The same procedure can be applied to the average gas density and its change with distance can be represented by the truncated Taylor series around the point x_2.

$$\overline{\rho}_G = \frac{1}{\delta x}\int_{x_2-\delta x}^{x_2} \rho_G\,dx\,, \tag{5}$$

$$\rho_G = \rho_{G2} + \left.\frac{\partial \rho_G}{\partial x}\right|_{x_2} (x - x_2)\,, \tag{6}$$

$$\overline{\rho}_G = \rho_{G2} + \frac{1}{2}\left.\frac{\partial \rho_G}{\partial x}\right|_{x_2} \delta x\,. \tag{7}$$

Now, δx is the last variable that remains to be addressed in Eq. (1). Assuming that in-situ gas velocities change with time at constant rates between t_1 and t_2, we have

$$x_2 = x_1 + \int_{t_1}^{t_2} v_{G1} + \frac{v_{G2} - v_{G1}}{\Delta t}(t - t_1)\,dt\,, \tag{8}$$

$$x_2' = x_1 + \int_{t_1+\delta t}^{t_2} v_{G1}' + \frac{v_{G2}' - v_{G1}'}{\Delta t - \delta t}(t - t_1 - \delta t)\,dt\,. \tag{9}$$

In the above equations, v_{G1} and v_{G2} represent the velocities of the top cross-sectional surface at time t_1 and t_2, respectively. The corresponding velocities of the bottom cross-sectional surface are v'_{G1} and v'_{G2} as defined below,

$$v_{G1}' = v_{G1} + \frac{\partial v_{G1}}{\partial t}\delta t\,, \tag{10}$$

$$v_{G2}' = v_{G2} - \frac{\partial v_{G2}}{\partial x}\delta x\,. \tag{11}$$

Finally, the small length δx is given by

$$\delta x = x_2 - x_2' = \frac{(v_{G1} + v_{G2} - \frac{\partial v_{G1}}{\partial t}(\Delta t - \delta t))\delta t}{2 - \frac{\partial v_{G2}}{\partial x}(\Delta t - \delta t)} \tag{12}$$

If Eqs. (4), (7) and (12) are substituted into Eq. (1), then, α_2 at the limit as $\delta t \to 0$ is given as,

$$\alpha_2 = \frac{W_{G1}\,(2 - \frac{\partial v_{G2}}{\partial x}\Delta t)}{\rho_{G2}\,A_p\,(v_{G1} + v_{G2} - \frac{\partial v_{G1}}{\partial t}\Delta t)}\,. \tag{13}$$

Thus α_2 refers to a differential volume element with cross-sectional area A_p and represents the instantaneous gas void fraction at a given space point in the pipe.

Eq. (13) is not affected by the truncation errors of the Taylor series in Eqs. (3), (6) and (10) because of the limit operation. This condition has been verified by using the software Mathematica up to 3rd order truncated Taylor series. However, the similar verification could not be made for Eq. (11). Furthermore, its accuracy will depend on how accurately the partial derivatives $\frac{\partial v_{G2}}{\partial x}$ and $\frac{\partial v_{G1}}{\partial t}$ are translated in the finite difference scheme.

As a part of verification of the Eq. (13), the steady state flow condition can be checked as a particular case,

$$\alpha_{2ss} = \frac{W_G}{\rho_{G2}\, A_p\, v_{G2}} . \tag{14}$$

Under the steady state flow condition Eq. (13) will give the same result as the Eq. (14), which is conservative, only if the following relation is true,

$$v_{G2} = \frac{v_{G1} + v_{G2}}{2 - \left.\frac{\partial v_{G2}}{\partial x}\right|_{x_2} \Delta t} . \tag{15}$$

The relation (15) can be verified as true by manipulation of the partial derivative $\frac{\partial v_{G2}}{\partial x}$ as follows. The definition of material derivative (meaning that the time rate of change is reported as one moves with the "material"), applied to the in-situ velocity of gas phase, is given by,

$$\frac{Dv_G}{Dt} = \frac{\partial v_G}{\partial t} + v_G \frac{\partial v_G}{\partial x} . \tag{16}$$

Then,

$$\frac{\partial v_{G2}}{\partial x} = \frac{1}{v_{G2}} \left(\frac{v_{G2} - v_{G1}}{\Delta t} - \frac{\partial v_{G2}}{\partial t} \right) . \tag{17}$$

For steady state, $\frac{\partial v_{G2}}{\partial t}$ and $\frac{\partial v_{G1}}{\partial t}$ become zero, and then, the relation (15) is satisfied by substitution of $\frac{\partial v_{G2}}{\partial x}$ with Eq. (17).

The derivation for instantaneous differential α was based on the conserved mass of gas, and its final form (13) degenerates to (14) under steady state condition. But the strict conservation of mass of gas can not be guaranteed under the transient flow condition in the finite difference model. This is the main drawback of the explicit calculation of α .

Nevertheless, there is one practical mechanism to control the problem of non-conservative formulation for α . Under the gas tracking numerical scheme the conserved gas mass content in each numerical cell is known throughout the simulation. This information can be used to keep the values of differential α within a reasonable conservative range.

Holdup Calculation

The instantaneous gas void fraction α_2 calculated in Eq. (13) depends on the estimate of the current in-situ gas velocity v_{G2}, but in-situ gas velocity v_{G2} itself depends on the gas void fraction α_2. So we need some closure relationship between gas velocity v_{G2} and void fraction α_2, or holdup.

Given in-situ gas velocity v_{G2} and gas void fraction α_2 the superficial gas velocity v_{SG2} can be calculated. And also superficial liquid velocity v_{SL2} can be obtained from liquid mass balance upon Eulerian remapped numerical grid as in Eq. (18),

$$v_{SL2} = v_{SL1} + \frac{\partial \alpha}{\partial t} \Delta x . \tag{18}$$

Liquid and gas superficial velocities calculated based on the estimated in-situ gas velocity will allow us to employ a steady state mechanistic two-phase flow model to calculate a new gas void fraction value. The closure is achieved if the two void fraction values match after an iterative process.

The mechanistic two-phase model best suited for the purpose is TUFFP Unified model because of the relatively smooth transition between different flow regimes and inclinations of flow path.

Tests performed using Unified model as liquid holdup closure model showed that it's not practical to make calls to that code in it's native form. The impeding factors are dramatic loss of simulation speed and stability. The alternative solution has been to generate a multidimensional interpolation table of holdup based on Unified model.

The number of interpolation parameters should be at least 10: Inclination angle; Diameter; Superficial gas velocity; Superficial liquid velocity; Gas density; Liquid density; Gas viscosity; Liquid viscosity; Roughness; and Surface tension. However the number of the parameters had to be reduced to 6, dropping the last 4 items from the list above, because of the computational limitations. The final version of the 6 dimensional table of holdup contains over 4.5 million numbers of double precision. Also one more table of the same size has been made for frictional pressure drop. The two tables require more than 12 hours to be generated using a fast computer.

Figures 3 and 4 are graphical representation of two dimensional sub-tables for liquid holdup. The transient simulation results using the interpolation tables are as fast as simple drift-flux model, and smoothening effect of the table makes the simulation stable.

Momentum Balance

The momentum balance can be applied on the remapped Eulerian numerical grid resulting from the Lagrangian step. The TUFFP Unified model can provide pressure drop components which can be combined with the rate of mixture momentum in/out and change of momentum with time inside the control volume.

The frictional pressure drop is read from the interpolation table based on the Unified model. The gravitational pressure drop is calculated using the holdup values read from the other interpolation.

Numerical Solution Strategy

The basic numerical solution strategy for one cell can be as shown in the Fig. 5. Lagrangian calculation of gas void fraction enables the calculation of superficial liquid velocity by means of mass balance equation on the Eulerian grid. Then, a new estimate of in-situ gas velocity can be obtained through a mechanistic two-phase model. This process is repeated until convergence on the value of v_G. Then, the momentum balance is applied to calculate the new estimate of pressure. The whole procedure is repeated until convergence is reached on the value of pressure p. The flow diagram of the process is shown in the Fig. 6.

Simulation of severe slugging

As the first step for validating the transient model, some simulations have been performed for severe slugging phenomena. Data for one of the sample cases are as follow:

1. Flow line of 5–in. ID, 10000 ft long with an inclination angle of -5.0°
2. Riser of 5–in. ID, 5987.5 ft long with an inclination angle of 90°
3. Liquid input of constant 2000 stb/d
4. Gas input of constant 1000 mscf/d
5. Fluids are water and natural gas

Figure 7 shows the liquid and gas flowrates at the surface under unstable situation. The same system becomes stabilized with gas injection of 1000 mscf/d at the riser base starting at 11 hour time point. Later the injection rate is reduced to 500 mscf/d maintaining the system stable with a small oscillation.

Problems of Current Model

In some simulation cases for severe slugging phenomenon, there were seemingly wrong results as shown in the Fig. 8. Investigations into the problem showed that the current model can not deal with the transition between countercurrent flow and cocurrent backward flow. Particularly, when the gas at the bottom of the riser reaches to stagnation situation of the falling liquid, it can not gain a positive or negative velocity even if new conditions favored some gas movement. The current model uses past time gas velocity to move the gas cells.

After time consuming efforts the problem could not be solved. As an alternative, “tank model” for gas has been tested, considering the continuous gas volume along the pipe where stratified flow pattern occurred. If it worked, the model could simulate the TUFFP severe slugging test facility. But severe instability of simulation was the result of the modifications, because of the continuous volume changed depending on the flow pattern map during the convergence process.

Currently the problem solving is requiring a major restructuring of the model and adding one more level of iteration to make gas movement totally implicit. That means the new gas velocity at the current time step will be used to calculate the gas cell movement.

Future Work

1. Simulation of water-oil segregation during shut-in.
2. Comparison with experimental test.
3. Final report.

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3. Lufkin, E. A, Fawley, J. F..: “The Piecewise-Linear Predictor-Corrector Code: a Lagrangian-Remap Method for Astrophysical Flows,” ApJS, 88, 569-588, 1993
4. Tengesdal, J. Ø.: “Investigation of Self-lifting Concept for Severe Slugging Elimination in Deep-Water Pipeline/Riser Systems,” Ph.D. Thesis, The Pennsylvania State University, 2002

Nomenclature

Variable	Description
A	area
m	mass
t	time
x	distance
p	pressure
v	velocity
W	mass flow rate
	Greek letters
α	gas void fraction
Δ	difference operator
δ	small difference operator
	Subscripts
$1,2$	time or position 1, 2
G	gas phase
p	pipe
ss	steady state
SG	superficial gas
SL	superficial liquid

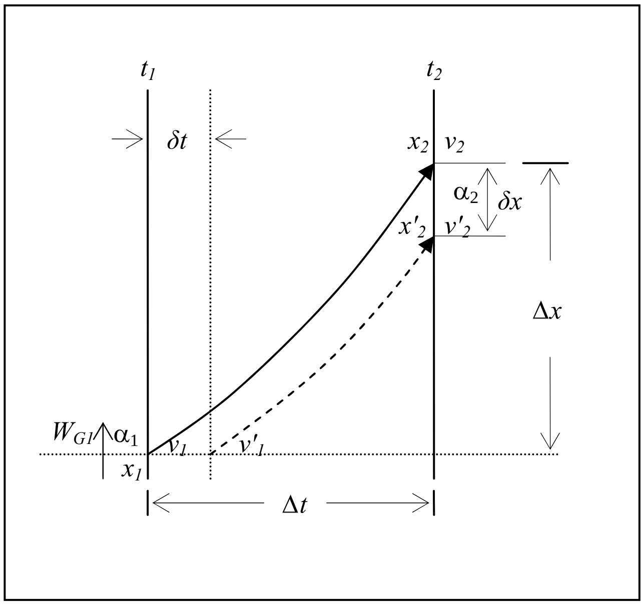


Figure 1 – Schematic of gas mass balance

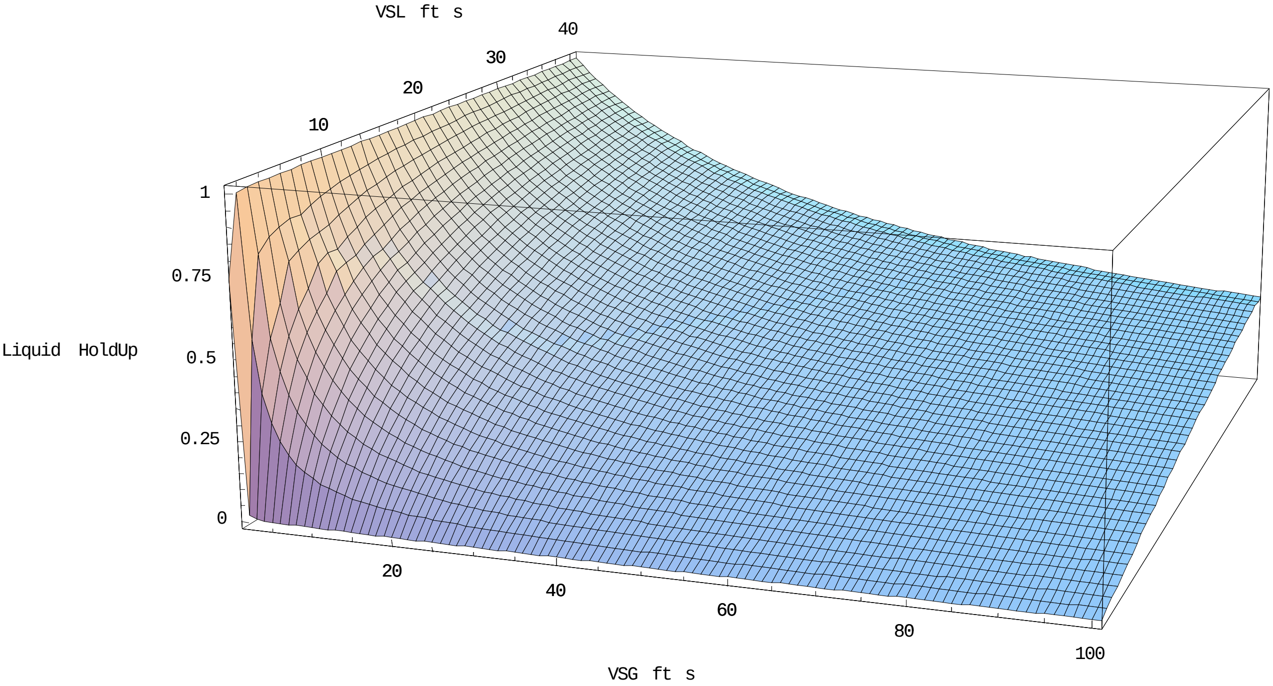


Figure 3 – Plot of liquid holdup table for horizontal flow based on Unified model.

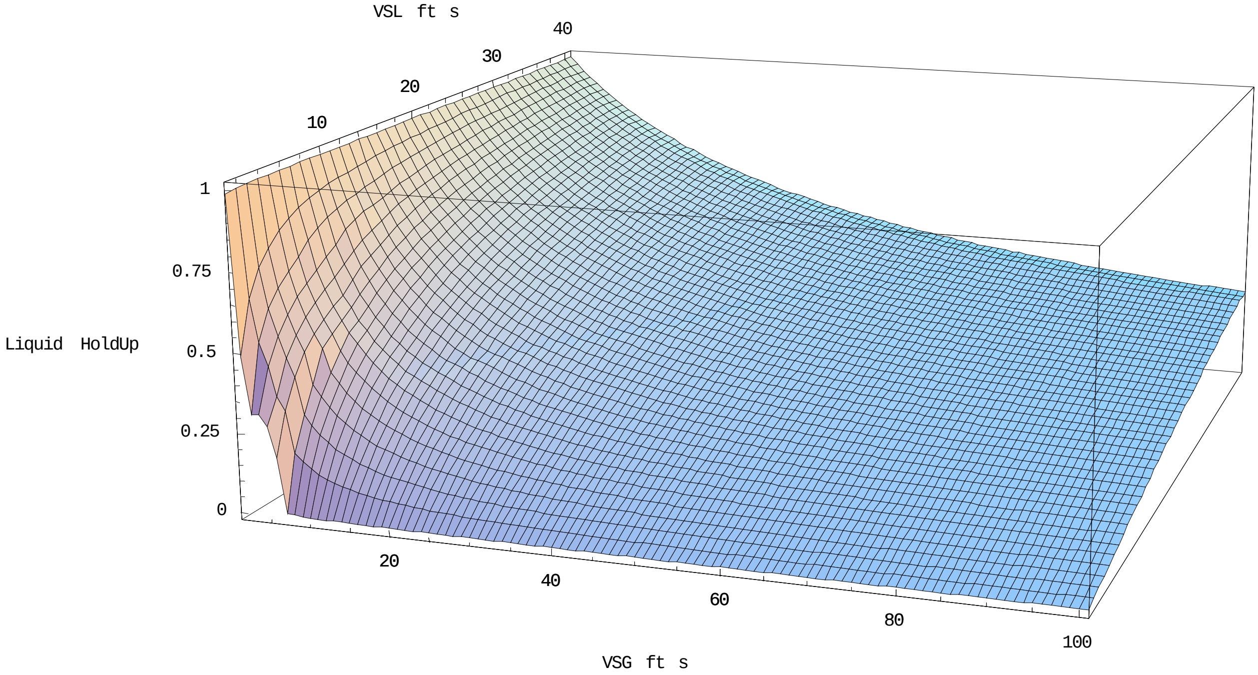


Figure 4 – Plot of liquid holdup table for vertical flow based on Unified model.

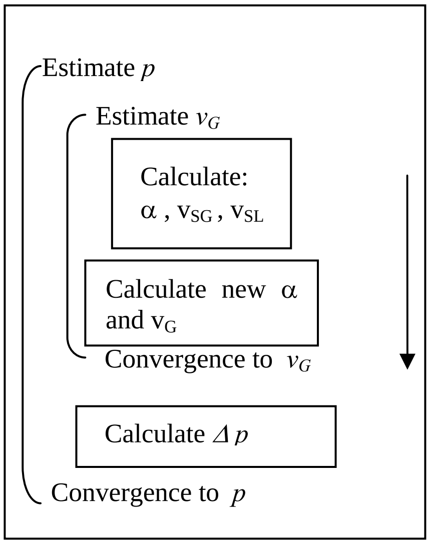


Figure 5 – Numerical solution diagram

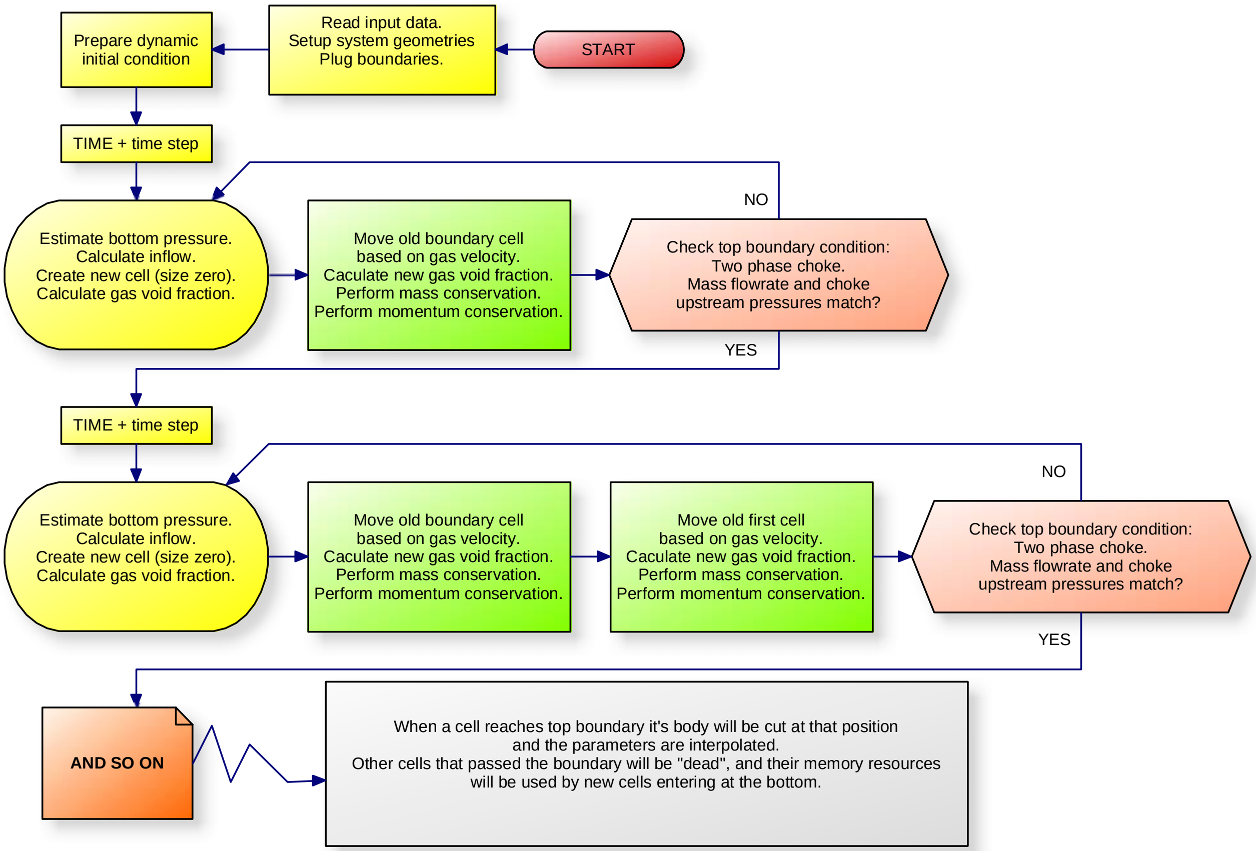


Figure 6 – Computational methodology

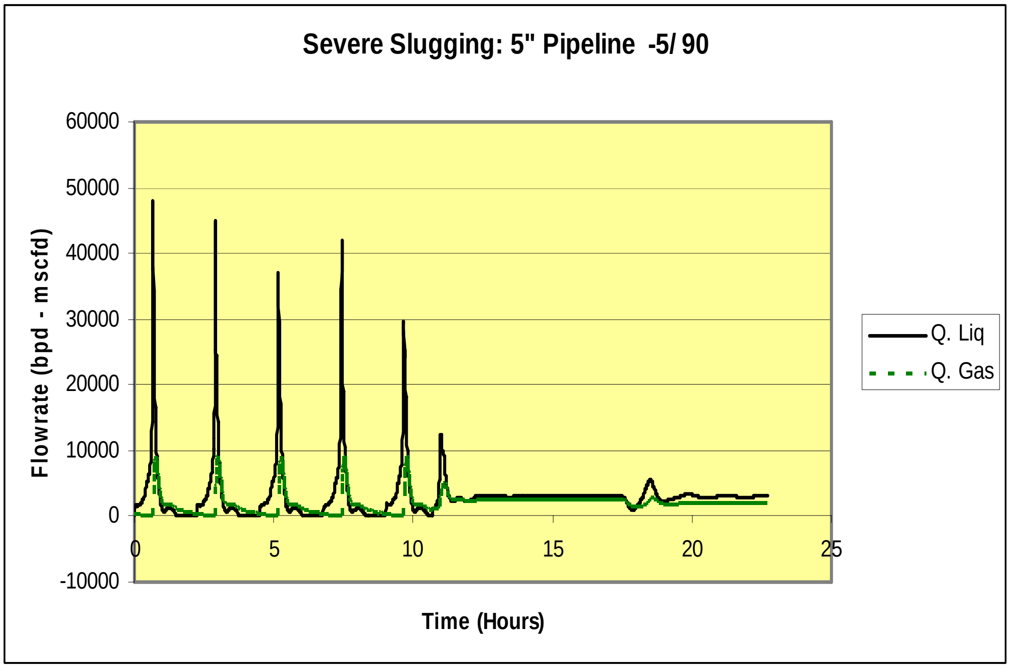


Figure 7 – Severe slugging simulation for 5-in. ID pipeline with -5° flow line and 90° riser.

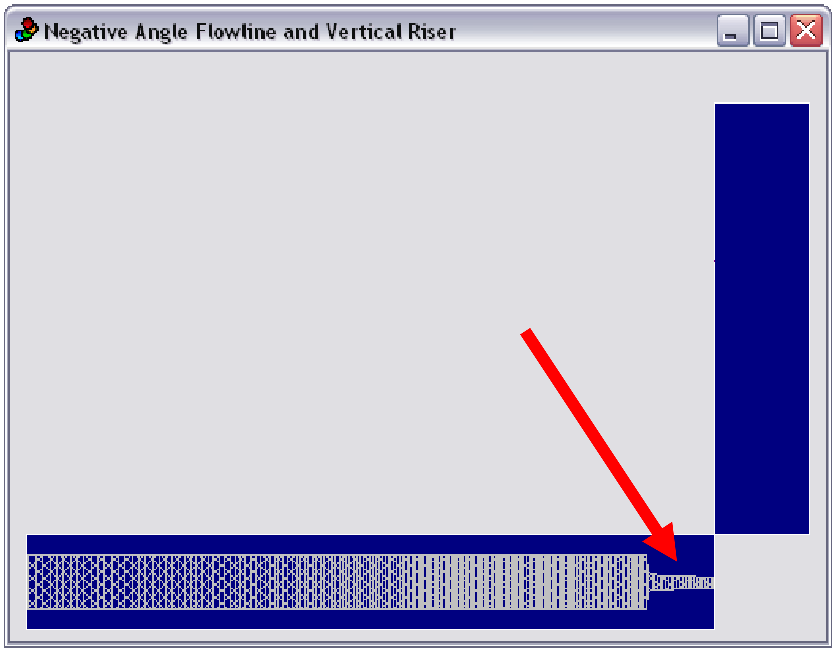
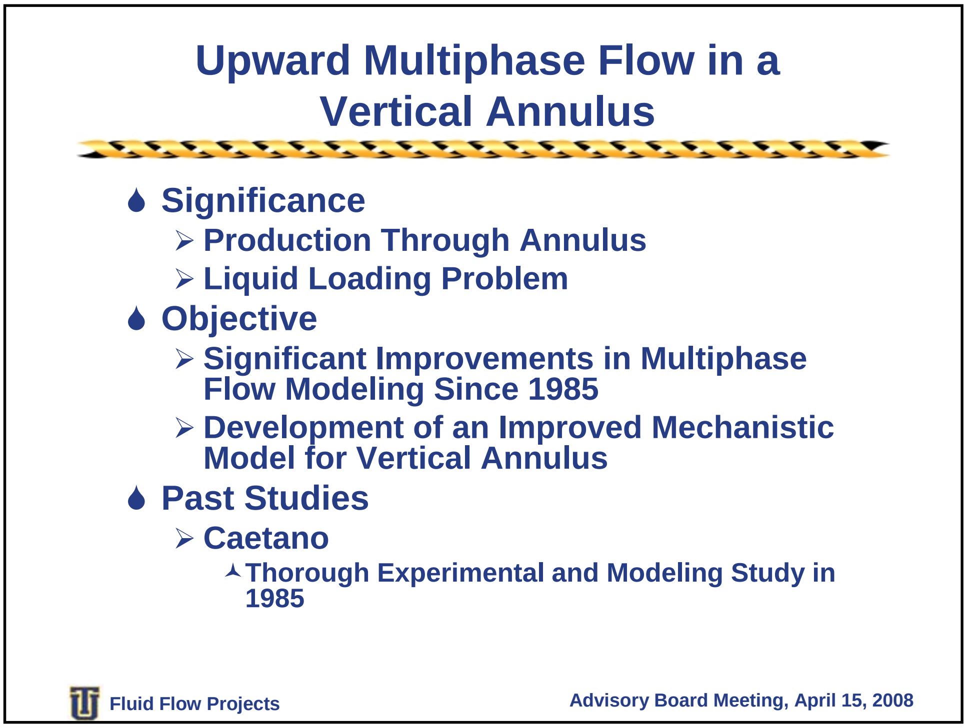
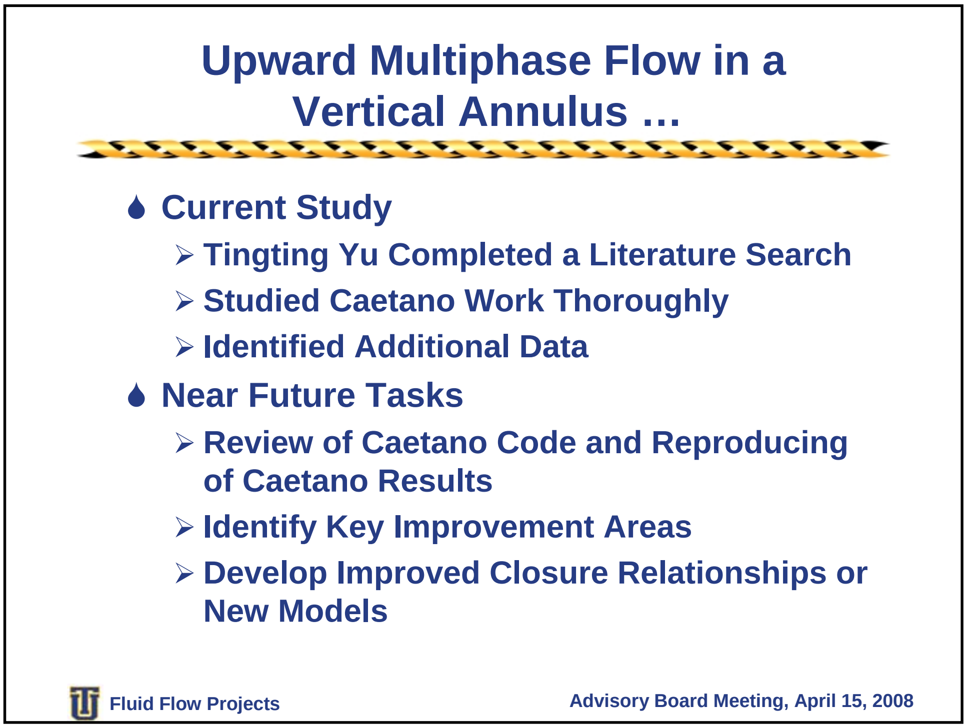


Figure 8 – Severe slugging simulation showing gas cells unable to move at the elbow



Upward Multiphase Flow in a Vertical Annulus

- Significance
  - Production Through Annulus
  - Liquid Loading Problem
- Objective
  - Significant Improvements in Multiphase Flow Modeling Since 1985
  - Development of an Improved Mechanistic Model for Vertical Annulus
- Past Studies
  - Caetano
    - Thorough Experimental and Modeling Study in 1985



Upward Multiphase Flow in a Vertical Annulus …

- Current Study
  - Tingting Yu Completed a Literature Search
  - Studied Caetano Work Thoroughly
  - Identified Additional Data
- Near Future Tasks
  - Review of Caetano Code and Reproducing of Caetano Results
  - Identify Key Improvement Areas
  - Develop Improved Closure Relationships or New Models

Fluid Flow Projects

Modeling of Gas-Liquid Flow in Upward Vertical Annuli

Tingting YU

Advisory Board Meeting, April 15, 2008

Outline

- Objectives
- Introduction
- Literature Review
- Flow Pattern Transition and Hydrodynamic Models for Annuli
- Research Plan

Objectives

- Theoretically Investigate Gas-Liquid Fluid Flow in Upward Vertical Concentric and Eccentric Annuli
- Analyze Data from Previous Experimental Study and Develop a New Model for Two-Phase Flow in Upward Annuli

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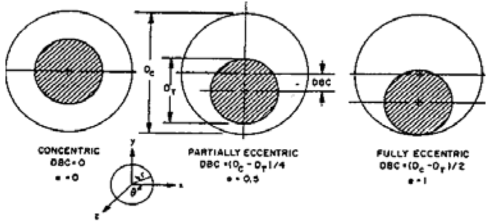
Introduction

- Flow through Annuli is Encountered in Many Applications
  - Wells under Various Types of Artificial Lifts
  - Gas Well Production
- Many Oil Wells with High Production Rates Produce through the Casing-Tubing Annulus
- Important to Study and Understand Flow in Annuli

Introduction…

- Annulus is Characterized by the Existence of Two Circular Pipes
- Two Geometrical Parameters:

$$K = \frac{d_T}{d_C} \qquad e = \frac{2D_{BC}}{(d_C - d_T)}$$



Annulus Configuration

Literature Review

- Kelessidis (1986)
    - Flow Pattern Transition Models for Upward Gas-Liquid Flow in Concentric and Eccentric Annuli
- Caetano et al. (1992)
    - Flow Pattern Transition and Hydrodynamic Models for Each Flow Pattern for Upward Vertical Concentric and Fully Eccentric Annuli
- Hasan and Kabir et al. (1992)
    - Flow Pattern Transition Models in Inclined Annuli

Literature Review…

- Lage et al. (2000)
    - Mechanistic Model for Horizontal and Slightly Deviated Fully Eccentric Annulus
- Sunthankar (2002)
    - Flow Pattern Transition Model for Horizontal and Near-Horizontal Annulus
- Omurlu et al. (2007)
    - Mechanistic Model for Two-Phase Flow in Horizontal Fully Eccentric Annulus

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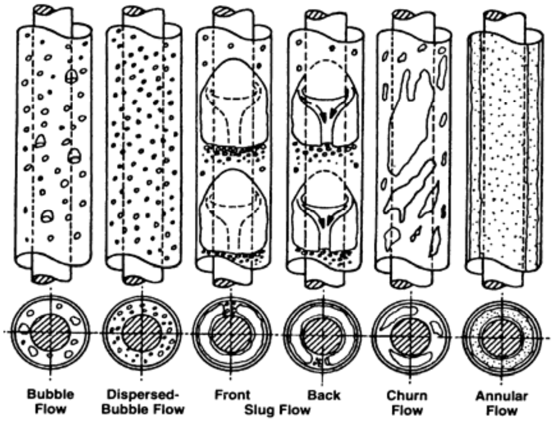
Literature Review Summary

- No Research on Two-Phase Flow Modeling in Vertical Annulus Since Caetano et al. (1992)
- Advances in Upward Pipe Modeling
    - Barnea (1986) Unified Model
    - Gomez et al. (2000) Unified Mechanistic Model
    - Kaya et al. (2001) Mechanistic Model
    - Zhang et al. (2003) Unified Model

Flow Patterns in Annulus (Caetano et al., 1992)

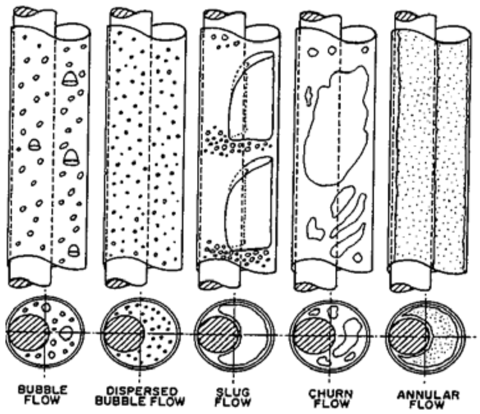
- Bubble Flow
- Dispersed Bubble flow
- Slug Flow
- Churn Flow
- Annular Flow

Flow Patterns in Concentric Annulus



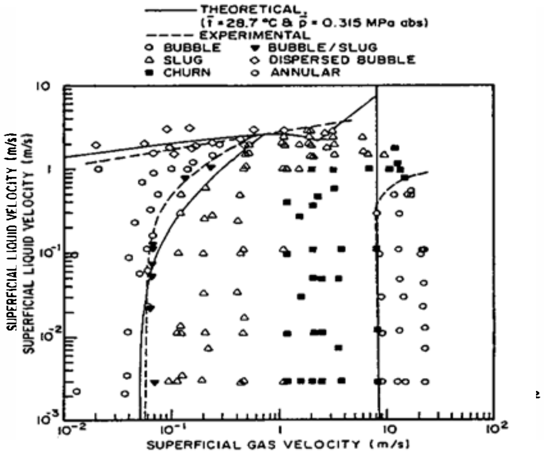
Caetano et al.(1992)

Flow Patterns in Fully Eccentric Annulus



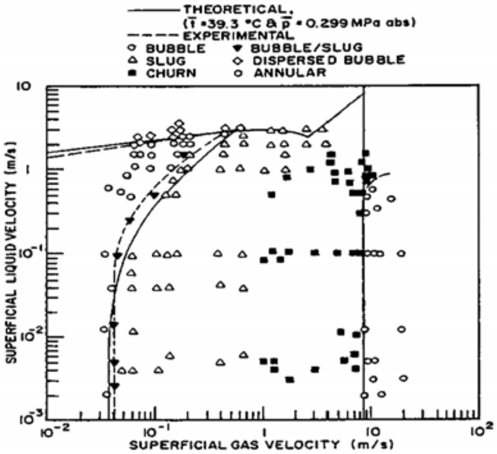
Caetano et al. (1992)

Flow Pattern Map-Concentric Annulus



Caetano, et al. (1992)

Flow Pattern Map-
Fully Eccentric Annulus



Caetano, et al. (1992)

Bubble/Slug Flow Transition

- **Bubbly/Slug Transition**
  - **Concentric Annulus**

$$V_{SG} = 0.25V_{SL} + 0.306\left[\frac{(\rho_L - \rho_G)g\sigma}{\rho_L^{\ 2}}\right]^{1/4}$$

  - **Fully Eccentric Annulus**

$$V_{SG} = \frac{V_{SL}}{5.67} + 0.230\left[\frac{(\rho_L - \rho_G)g\sigma}{\rho_L^{\ 2}}\right]^{1/4}$$

Bubble/Slug Flow Transition…

- **Bubbly/Dispersed Bubble Transition Criteria:**

$$2\left[\frac{0.4\sigma}{(\rho_L-\rho_G)g}\right]^{1/2}\left(\frac{\rho_L}{\sigma}\right)^{1/5}\left(\frac{2}{d_H}\right)^{2/5} f^{2/5}V_M^{\ 6/5}=0.725+4.15\left(\frac{V_{SG}}{V_M}\right)^{1/2}$$

- **Dispersed Bubble/Slug Transition**

$$V_{SG}=1.083V_{SL}+0.796\left[\frac{(\rho_L-\rho_G)g\sigma}{\rho_L^{\ 2}}\right]^{1/4}$$

Annular Transition

- **Annular Transition**

$$\frac{V_{SG}\rho_G^{\ 1/2}}{\left[\sigma g(\rho_L-\rho_G)\right]^{1/4}}=3.1$$

- **No Slug/Churn Transition is Given in This Model**

Hydrodynamic Model

- Bubble Flow Model

$$V_s = \frac{V_{SG}}{1-H_L} - \frac{V_{SL}}{H_L} \qquad V_o = 1.53\left[\frac{(\rho_L - \rho_G)g\sigma}{\rho_L^{\,2}}\right]^{1/4} H_L^{\,n}$$

Given by Harmathy (1955)

Slug Flow Model

- Two Models Developed for Developing Slug Flow and Fully Developed Slug Flow
- Both Models Based on Mass Balance and Momentum Balance Equation
- Important Closure Relationship: Taylor Bubble Rise Velocity

Annular Flow Model

- Model Developed for Equilibrium Fully Developed Flow
- Model Based on Momentum Conservation and Phase Continuity for Two Liquid Films and Gas Core
- Two Important Closure Relationships: Liquid Film Thickness and Interfacial Fanning Friction Factor

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Research Plan

- Apply Pipe Flow Models in Annulus by Using Geometrical Diameter
  - Hydraulic Diameter

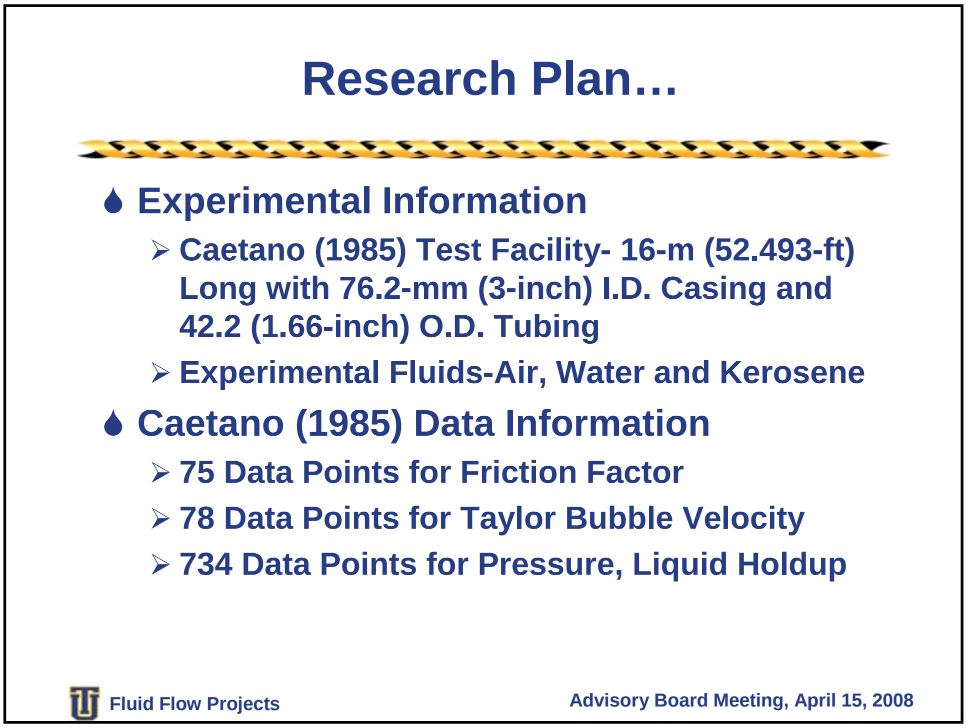
$$d_h = d_C - d_T$$

  - Representative Diameter

$$d_r = \sqrt{(d_C^{\,2} - d_T^{\,2})}$$

  - Equi-periphery Diameter

$$d_{EP} = d_C + d_T$$



Research Plan…

- Experimental Information
  - Caetano (1985) Test Facility- 16-m (52.493-ft) Long with 76.2-mm (3-inch) I.D. Casing and 42.2 (1.66-inch) O.D. Tubing
  - Experimental Fluids-Air, Water and Kerosene
- Caetano (1985) Data Information
  - 75 Data Points for Friction Factor
  - 78 Data Points for Taylor Bubble Velocity
  - 734 Data Points for Pressure, Liquid Holdup

Research Plan…

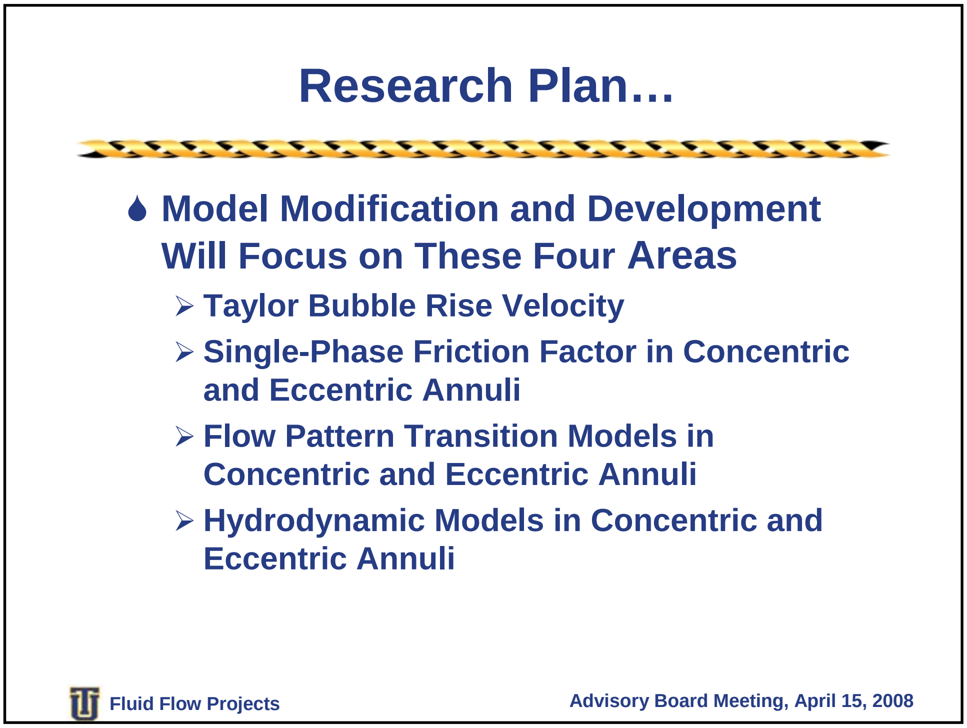
- Test Condition Ranges (Caetano, 1985)
  - Air and Water in Concentric Annulus:
    - Vsg: 0.037-22.859-m/s
    - VsL: 0.002-3.051-m/s
  - Air and Water in Fully Eccentric Annulus:
    - Vsg: 0.023-22.793-m/s
    - VsL:0.002-3.529-m/s
  - Air and Kerosene in Concentric Annulus:
    - Vsg: 0.029-22.531-m/s
    - VsL: 0.003-1.994-m/s

Research Plan…

- Kelessidis (1986) Data Information
    - Taylor Bubble Rise Velocity
    - Liquid and Gas Velocity
- Literature Review is Underway, More Experimental Data May Be Found

Fluid Flow Projects

Advisory Board Meeting, April 15, 2008



Research Plan…

- Model Modification and Development Will Focus on These Four Areas
    - Taylor Bubble Rise Velocity
    - Single-Phase Friction Factor in Concentric and Eccentric Annuli
    - Flow Pattern Transition Models in Concentric and Eccentric Annuli
    - Hydrodynamic Models in Concentric and Eccentric Annuli

Fluid Flow Projects

Advisory Board Meeting, April 15, 2008

Project Schedule

Literature Review	June 2008
Model Development	August 2008
Model Modifications	December 2008
Final Report	May 2009

Questions & Comments

Questions ?

Modeling of Gas-Liquid Flow in an Upward Vertical Annulus

Tingting YU

PROJECTED COMPLETION DATES:

Literature Review.. June 2008
Model Development .... August 2008
Model Validation.. December 2008
Final Report.. May 2009

Objectives

The objectives of this study are:

- Theoretically investigate upward gas-liquid two-phase flow in concentric and eccentric annuli
- Analyze data from a previous experimental study (Caetano (1985)) and develop a new model for gas-liquid two-phase flow in an annulus

Introduction

An annulus is formed by a pipe being located inside a larger pipe. Fluid flows through the area bounded by the outer pipe inner wall and the inner pipe outer wall. There are two important parameters to identify this configuration: annulus pipe diameter ratio and the degree of eccentricity.

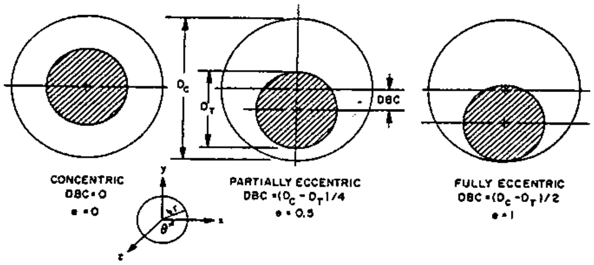


Fig. 1 Annuli configuration

The pipe diameter ratio is given by:

$$K = \frac{d_T}{d_C} \tag{1}$$

where d_T is the outer diameter of tubing and d_C is the inner diameter of casing. The degree of eccentricity accounts for the displacement of the inner pipe center from the outer pipe center and is expressed by:

$$e = \frac{2DBC}{(d_C - d_T)} \tag{2}$$

DBC is the distance between the two pipe centers.

In the petroleum industry, multiphase flow in wells normally occurs in a tubing string. However, many oil wells with high production rates produce through the casing-tubing annulus. This trend can be dictated by economics, multiple completions and regulated production rates. Although the number of these wells is small compared with all producing wells, these "casing flow" wells still account for a significant part of the world oil production.

Many applications of casing flow in the oil industry are also found for various types of artificial lift. In sucker rod pumping wells, a rod string is installed inside the tubing string to connect the prime mover unit on the surface to the pump at the bottom of the well. The fluids are pumped upward through the tubing-rod string annulus.

Another application of flow through an annulus is found in gas well production. In order to remove or "unload" undesirable liquids that can accumulate at the bottom of these wells, a siphon tube is often installed inside the tubing string. The normal permanency of the siphon tube in the tubing string requires the fluids to flow upward through the tubing string-siphon tube annulus.

Most researchers have treated the annulus based on the hydraulic diameter concept. The hydraulic diameter is four times the area for flow divided by the wetted perimeter. For annulus configurations

$$d_H = d_C - d_T$$

where d_H is hydraulic diameter.

However, the hydraulic diameter is not always the most representative characteristic dimension for flow in an annulus. Omurlu and Evren introduced a “representative diameter” for a fully eccentric annulus, which they claimed worked better than hydraulic diameter. For annular configurations:

$$d_r = \sqrt{d_C{}^2 - d_T^2}$$

where d_r is the representative diameter.

Sadatomi et al. (1982) model used the equi-periphery diameter to calculate the Taylor bubble rise velocity. Thus,

$$d_{EP} = d_C + d_T$$

where d_{EP} is the equi-periphery diameter.

Among these three annulus diameters, the hydraulic diameter is most widely used and equi-periphery diameter has only been applied in Taylor bubble velocity calculation. In the present study, these three diameters will be tried and evaluated to select the best one for the new model.

The objective of this study is to develop a new model for gas-liquid two-phase flow in concentric and eccentric annuli. Since many advances for two-phase flow modeling in pipes have been made in recent years, these improvements will be incorporated in the new models by using all three annulus diameters. Comparisons between previous experimental data (Caetano *et al.* (1985)) and model predictions will be carried out to determine which of the annulus diameters performs best.

Literature Review

Extensive theoretical and experimental studies have been carried out to investigate two-phase flow through pipes. The proposed methods can be grouped into two categories: empirical correlations and mechanistic models. The empirical correlations often ignore the flow patterns, and treat the two-phase flow as a pseudo single-phase fluid flow or as a flow of two separated fluids. In mechanistic models, the flow mechanisms and physics of two-phase fluid systems are examined independently for each flow pattern. As knowledge of flow behavior of two-phase fluid systems improved, comprehensive and unified models were developed.

For two-phase flow through annular geometries, several studies have been published in recent years.

Sadotomi *et al.* (1982) developed a friction factor correlation, flow pattern maps and predicted Taylor bubble rise velocity for air-water flow through vertical noncircular channels. They developed flow pattern transition criteria based on the value of the slug interval, which refers to the length from the nose of a large gas bubble to that of the succeeding one. This method is similar to the Zhang *et al.* (2003) flow pattern transition model, which is based on the liquid film length.

Kelessidis (1986) experimentally and theoretically investigated vertical upward gas-liquid flow in concentric and eccentric annuli. He studied the factors that affect the Taylor bubble rise velocity, i.e the length and the shape of the Taylor bubble and the liquid velocity around the Taylor bubble. His flow pattern transition criteria were based on Taitel et al. model with some modifications. He developed different transition models for concentric and eccentric annuli and analyzed the effect of inner tube diameter and eccentricity on flow pattern transitions.

Hasan and Kabir (1992) conducted two-phase flow experiments in inclined annular geometries and developed flow pattern transition models. The drift-flux approach was adapted to the transitions and slip between phases, and void fraction was calculated for each flow pattern. The effect of annulus dimension on flow pattern transitions was also considered in this study.

Caetano *et al.* (1992) conducted experiments in concentric and fully eccentric annuli. They developed flow pattern transition models for concentric and fully eccentric annulus based on the Taitel et al. model. Hydrodynamic models for bubble flow, slug flow and annular flow were presented in this study. Important closure relationships, including Taylor bubble rise velocity and single-phase friction factor for an annulus were analyzed by considering the annulus geometry.

Lage *et al.* (2000) developed a mechanistic model for two-phase flow in horizontal and slightly deviated fully eccentric annuli. A procedure for predicting flow pattern and a set of independent models for calculating gas fraction and pressure drop in stratified, intermittent, dispersed bubble and annular flow were included in this model.

Sunthankar (2002) modified the mechanistic model developed by Taitel and Dukler (1976) to predict the flow patterns for horizontal and near-horizontal flow in an annulus.

Omurlu and Evren (2007) developed a mechanistic model to predict flow pattern transitions and pressure drop in a fully eccentric horizontal annulus. They introduced a “representative diameter” term and claimed it yielded more accurate results than the hydraulic diameter.

The above literature review for two-phase flow in an annulus shows that several methods exist to predict flow pattern transitions in annuli, but not other characteristics. Most investigators applied flow pattern transition models and hydrodynamic models in a single in an annulus with various modifications. Since many improvements in flow pattern transition models and hydrodynamic models have been made in recent years, these advances can be applied in the present study. Several representative previous studies on upward gas-liquid pipe flow are listed below.

Barnea (1987) modified the Taitel *et al.* flow pattern transition model and developed a unified model for flow pattern transitions at all pipe inclinations.

Ansari *et al* (1994) developed a comprehensive model to predict flow behavior for upward two-phase flow. Flow pattern transitions and independent mechanistic models for predicting such flow characteristics as holdup and pressure drop in bubble, slug and annular flow were advanced in this model. The Barnea (1987) and Caetano *et al.* models were adopted in this model with modifications.

Gomez *et al* (2000) developed a unified model for predicting flow pattern, liquid holdup and pressure drop in pipes from horizontal to vertical angles. This model presented a new criterion for eliminating discontinuity problems and provides smooth transition between different flow patterns.

Kaya *et al* (2001) advanced a mechanistic model for two-phase flow in deviated wells. He introduced a hydrodynamic model for bubbly flow.

Zhang et al developed a unified model for gas-liquid pipe flow, which can be used for any inclination. This model is based on the dynamics of slug flow, which is located in the center of the flow pattern map. Flow pattern transitions from slug flow to other flow patterns were developed based on liquid film length. The momentum exchange between the slug body and the film zone was introduced into the momentum equations for slug flow by considering the entire film zone as a control volume. Discontinuities among the closure relationships were eliminated through careful selection and generalization.

Research Plan

1. Taylor Bubble Rise Velocity

Taylor bubble rise velocity is a critical factor in slug flow model and many investigators have conducted experiments to develop Taylor bubble rise velocity models. Caetano *et al.* (1992) used the Sadatomi *et al.* (1982) model. However, this model did not consider the effect of annulus eccentricity on the Taylor bubble rise velocity and from previous experimental data (Caetano (1985) and Kelessidis (1986)), Taylor bubble rise velocity in concentric annulus is higher than in an eccentric annulus. A new model for Taylor bubble rise velocity will be attempted in the present study.

2. Single-Phase Friction Factor

Frictional pressure drop accounts for an important part of overall pressure drop, and hence the calculation of friction factor is very critical. Due to the difference of geometries between an annulus and a circular pipe, friction factor equations need to be reconsidered. Caetano *et al.* determined friction factor by combining the continuity equation, the equation of motion and the Fanning equation in laminar flow. For turbulent flow, the Gunn and Darling (1963) approach was used to calculate friction factor.

Single-phase friction factor expressions for pipes will be used for annuli but with geometric diameters. The Caetano *et al.* friction geometric parameter for concentric and eccentric annulus will be used and the results will be compared and analyzed.

3. Flow Pattern Transitions

The Caetano *et al.* flow pattern transition criteria were based on the Taitel *et al.* (1980) model with some modifications. Prediction of the annular flow transition will be improved by considering instability of the liquid film and bridging of the gas core. The slug-churn flow transition may need to be included in the new model. Other flow pattern transitions might also be modified by considering the effect of eccentricity. The modified Caetano *et al.* flow pattern transition criteria will be reevaluated. The Zhang *et al.* (2003) unified model will also be evaluated by using the Caetano (1985) data. The two results will be compared and the better one will be chosen as the new flow pattern transition model.

4. Hydrodynamic Models

Hydrodynamic models for bubble, slug, churn and annular flow will be developed to predict liquid holdup and pressure drop. The Caetano *et al.* (1992) model will be reevaluated with new closure relationships and new characteristic diameters. The Zhang *et al.* unified model will also be evaluated with Caetano (1985) data with proper modifications by considering the annulus geometries. Results will be compared and appropriate improvements will be made.

References

Ansari, A.M., Sylvester, N.D. and Sarica, C.: “A Comprehensive Mechanistic Model for Upward Two-phase Flow in Wellbores”, *SPE J. Prod. and Fac.* (May 1994) 143.

Barnea, D.: “A Unified Model for Predicting Flow-Pattern Transition for the Whole Range of Pipe Inclinations”, *Intl, J. Multiphase Flow* 13, No, 1, 1-12 (1987).

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Kelessidis, C.: “Vertical Upward Gas-Liquid Flow in Concentric and Eccentric Annuli”, PhD Dissertation, U. of Houston, Houston, TX (1986).

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Omurlu, C.M. and Evren, M.O.: “Analysis of Two-Phase Fluid Flow through Fully Eccentric Horizontal Annuli”, Proceedings BHRG Multiphase Technology Conference, Edinburgh, UK (2007)

Sadatomi, M., Sato, Y. and Saruwatari, S.: “Two-phase Flow in Vertical Noncircular Channels”, *Int. J. Multiphase Flow* 8, 641-655 (1982).

Sunthankar, A.A.: “Study of the Flow of Aerated Drilling Fluids in Annulus under Ambient Temperature and Pressure Conditions” MS Thesis, U. Tulsa, Tulsa, OK (2002).

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Fluid Flow Projects

Business Report

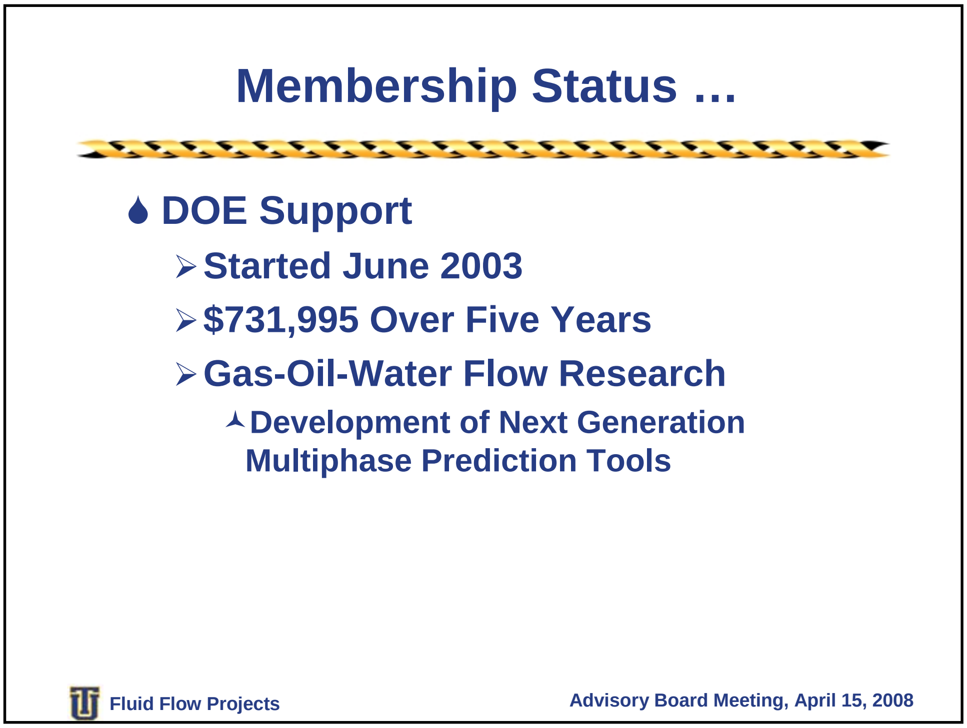
Cem Sarica

Advisory Board Meeting, April 15, 2008

Membership Status

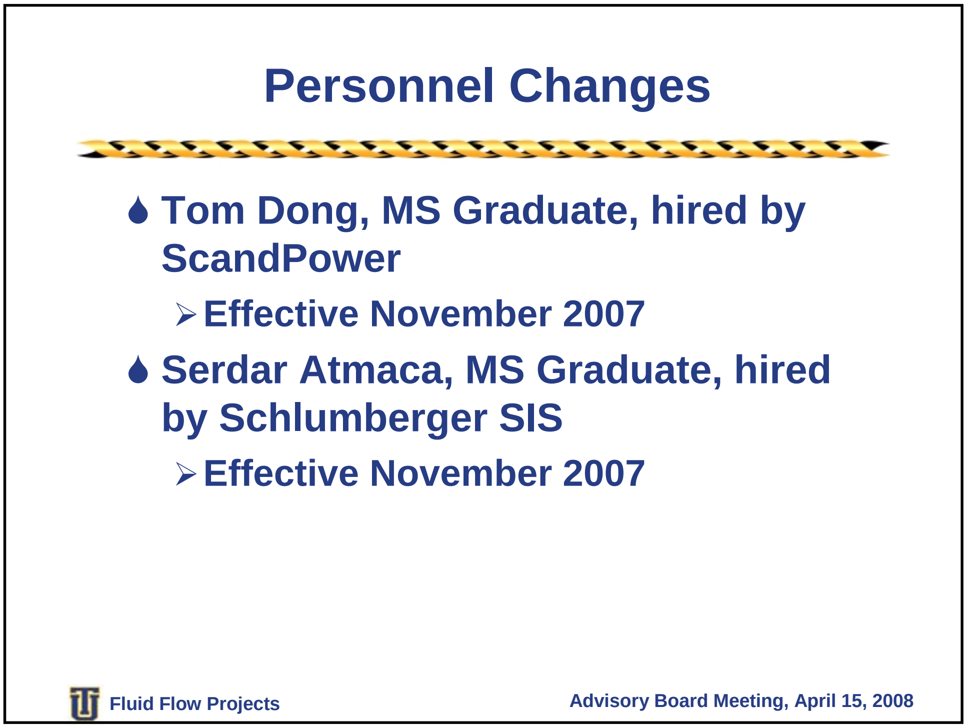
- Current Status
  - Membership Stands at 17
    - 16 Industrial and MMS
  - Efforts Continue to Increase Membership

Fluid Flow Projects   Advisory Board Meeting, April 15, 2008



Membership Status …

- DOE Support
  - Started June 2003
  - $731,995 Over Five Years
  - Gas-Oil-Water Flow Research
    - Development of Next Generation Multiphase Prediction Tools



Personnel Changes

- Tom Dong, MS Graduate, hired by ScandPower
  - Effective November 2007
- Serdar Atmaca, MS Graduate, hired by Schlumberger SIS
  - Effective November 2007

Conferences

- BHRg 2008 Production Technology Conference
  - Banff, Alberta, Canada June 4 – 6, 2008
  - Paper from TUFFP Research Projects
    - Gokcal, B. Al-Sarkhi, A., Sarica, C.: Effects of High Oil Viscosity on Drift Velocity for Horizontal Pipes

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Next Advisory Board Meetings

- Tentative Schedule
  - September 16, 2008
    - TUHOP Meeting
    - TUFFP Workshop
    - Facility Tour
    - TUHOP/TUFFP Social Function
  - September 17, 2008
    - TUFFP Meeting
    - TUFFP/TUPDP Reception
  - September 18, 2008
    - TUPDP Meeting
- ACAC, TU South Campus

Financial Report

- Year 2007 Closing
  - TUFFP Industrial Account
  - TUFFP MMS Account
  - TUFFP DOE Account
- Year 2008 Summary
  - TUFFP Industrial Account
  - TUFFP MMS Account
  - TUFFP DOE Account

Fluid Flow Projects

Advisory Board Meeting, April 15, 2008

2007 TUFFP Industrial Account Budget Summary

(Prepared April 8, 2008)

Anticipated Reserve Fund Balance on January 1, 2007		**644,242.26**
Income for 2007		
	2007 Membership Fees (15 @ $40,000 - excludes MMS)	**$600,000**
	2007 Membership Fees (1 @ 30,000)	**$30,000**
	2007 Membership Fees (1 @ 50,000)	**$50,000**
Total Budget		**1,324,242.26**

Projected Budget/Expenditures for 2007

		Budget	**Revised Budget 5/8/07**	**2007 Expenses**
90101 - 90110	Faculty Salaries	52,698.00	40,309.41	49,866.11
90600 - 90609	Professional Salaries	61,372.00	73,342.41	58,873.67
90700 - 90800	Technician	35,680.00	31,851.19	35,767.69
91000	Graduate Students - Monthly	50,100.00	50,100.00	46,769.84
91100	Students - Hourly	15,000.00	15,000.00	20,717.39
91800	Fringe Benefits (35%)	50,910.83	50,926.05	47,260.27
93100	General Supplies	3,000.00	3,000.00	4,629.09
93101	Research Supplies	100,000.00	100,000.00	82,998.83
93102	Copier/Printer Supplies	500.00	500.00	253.59
93104	Computer Software	4,000.00	4,000.00	1,801.79
93106	Office Supplies	2,000.00	2,000.00	1,343.24
93200	Postage/Shipping	500.00	500.00	1,491.06
93300	Printing/Duplicating	2,000.00	2,000.00	4,522.75
93400	Telecommunications	3,000.00	3,000.00	2,168.41
93500	Membership/Subscriptions	1,000.00	1,000.00	384.00
93600	Travel			153.81
93601	Travel - Domestic	14,000.00	14,000.00	6,622.77
93602	Travel - Foreign	10,000.00	10,000.00	4,768.83
93606	Visa		-	
93700	Entertainment (Advisory Board Meetings)	10,000.00	10,000.00	10,263.36
94803	Consultants		10,791.69	13,791.69
94813	Outside Services	20,000.00	20,000.00	9,652.55
95200	F&A (55.6%)	119,456.33	118,677.40	117,869.05
98900	Employee Recruiting	3,000.00	3,000.00	1,038.65
99001	Equipment	600,000.00	600,000.00	134,610.94
99002	Computers	8,000.00	8,000.00	19,190.13
99300	Bank Charges	40.00	40.00	18.00
81801	Tuition/Fees	30,306.00	30,306.00	34,377.00
81806	Graduate Fellowship			933.03
	Total Expenditures	**1,196,563.16**	**1,202,344.15**	**712,137.54**

Anticipated Reserve Fund Balance on December 31, 2007	**$ 612,104.72**

2007 MMS Account Summary

2007 TUFFP MMS Budget Summary
(Prepared April 8, 2008)

Reserve Balance as of 12/31/06	**$6,110**
2007 Budget	**40,000**
Total Budget	**46,110**

Projected Budget/Expenditures for 2006

		Budget	2007 Expenditures
91000	Students - Monthly	25,600.00	26,400.00
95200	F&A	14,233.60	14,388.00
81801	Tuition/Fees		
Total Anticipated Expenditures as of 12/31/07		**39,833.60**	**40,788.00**

Total Anticipated Reserve Fund Balance as of 12/31/07 **5,321.94**

2007 DOE Account Summary

2007 TUFFP DOE Budget
(PreparedApril 8, 2008)

Award Amount	**$731,995**
Amount Invoiced (June 1, 2003 - December 31, 2006)	**495,393.17**
Total Budget	**236,601.83**

Projected Budget/Expenditures for 2007

		2007 Budget	2007 Expenditures
90600	Professional Salary - Jones	8,281.00	8,250.40
90601	Professional Salary - Wang/Abdel	15,228.00	13,201.39
90602	Professional Salary - Graham	26,368.00	26,062.83
90702	Technician - Mechanical	3,037.00	3,155.42
91000	Graduate Students - Monthly	26,600.00	23,730.23
91800	Fringe Benefits (35%)	18,520.00	17,135.99
95200	F&A (51%)	40,454.71	37,944.14
Total Anticipated Expenditures as of 12/31/07		**138,488.71**	**129,480.39**

Anticipated Fund Balance on 12/31/07 **$ 107,121.44**

2008 TUFFP Industrial Account Budget Summary
(Prepared April 8, 2008)

Anticipated Reserve Fund Balance on January 1, 2008	**612,104.72**
Income for 2008	
2008 Membership Fees (15 @ $48,000 - excludes MMS)	**$720,000**
2008 Membership Fees (1 @ 38,000)	**$38,000**
Total Budget	**1,370,104.72**

Projected Budget/Expenditures for 2008

		Proposed Budget	**Revised Budget 4/8/07**
90101 - 90110	Faculty Salaries	28,474.96	25,913.18
90600 - 90609	Professional Salaries	96,359.54	90,719.42
90700 - 90800	Technician - Miller	24,228.72	21,582.14
91000	Graduate Students - Monthly	65,000.00	65,000.00
91100	Students - Hourly	15,000.00	15,000.00
91800	Fringe Benefits (35%)	49,190.86	45,610.86
93100	General Supplies	3,000.00	3,000.00
93101	Research Supplies	100,000.00	100,000.00
93102	Copier/Printer Supplies	500.00	500.00
93104	Computer Software	4,000.00	4,000.00
93106	Office Supplies	2,000.00	2,000.00
93200	Postage/Shipping	500.00	500.00
93300	Printing/Duplicating	2,000.00	2,000.00
93400	Telecommunications	3,000.00	3,000.00
93500	Membership/Subscriptions	1,000.00	1,000.00
93600	Travel		
93601	Travel - Domestic	10,000.00	10,000.00
93602	Travel - Foreign	10,000.00	10,000.00
93606	Visa		-
93700	Entertainment (Advisory Board Meetings)	10,000.00	10,000.00
94803	Consultants	16,000.00	16,000.00
94813	Outside Services	20,000.00	100,000.00
95200	F&A (55.6%)	127,359.15	121,327.40
98901	Employee Recruiting	3,000.00	3,000.00
99001	Equipment	200,000.00	500,000.00
99002	Computers	8,000.00	8,000.00
99300	Bank Charges	40.00	40.00
81801	Tuition/Fees	53,219.70	53,219.70
81806	Graduate Fellowship		-
	Total Expenditures	**851,872.93**	**1,211,412.70**

Anticipated Reserve Fund Balance on December 31, 2008	**$ 158,692.02**

2008 MMS Account Summary

2008 TUFFP MMS Budget Summary
(April 8, 2008)

Reserve Balance as of 12/31/07	**$5,322**
2008 Budget	**40,000**
Total Budget	**45,322**

Projected Budget/Expenditures for 2008

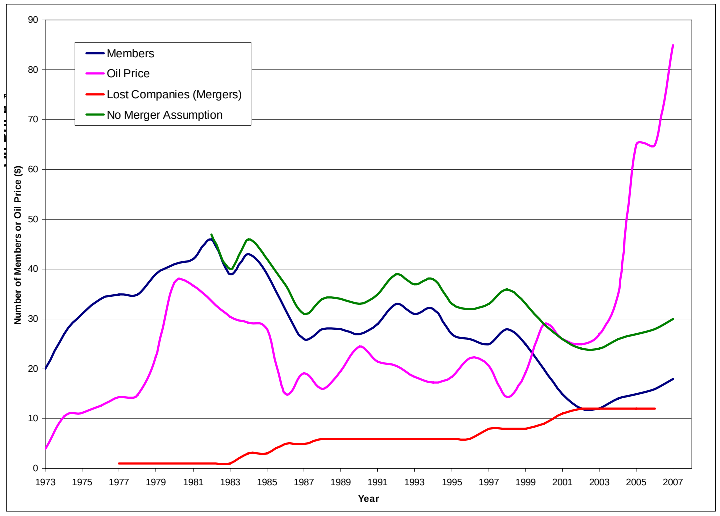
		Budget	
91000	Students - Monthly	28,800.00	
95200	F&A	16,012.80	
81801	Tuition/Fees		
Total Anticipated Expenditures as of 12/31/08		**44,812.80**	
Total Anticipated Reserve Fund Balance as of 12/31/08			**509.14**

2008 DOE Account Summary

2008 TUFFP DOE Budget
(Prepared April 8, 2008)

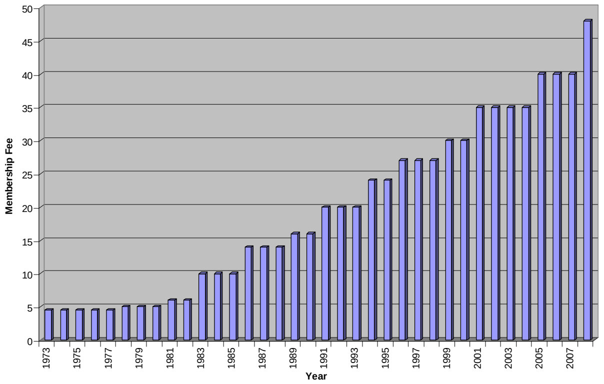
Award Amount			**$731,995**
Amount Invoiced (June 1, 2003 - December 31, 2007)			**624,873.56**
Total Budget			**107,121.44**
Projected Budget/Expenditures for 2008			
		2008 Budget	
90600	Professional Salary - Jones	6,279.00	
90601	Professional Salary - Wang/Abdel	22,958.33	
90602	Professional Salary - Graham	12,514.00	
90702	Technician - Mechanical	3,644.00	
90703	Technician - Mechanical	6,825.00	
91000	Graduate Students - Monthly	7,000.00	
91800	Fringe Benefits (33%)	17,232.50	
95200	F&A (51%)	30,202.50	
Total Anticipated Expenditures as of 5/31/08		**106,655.33**	
Anticipated Fund Balance on 5/31/08			**$ 466.11**

History – Membership



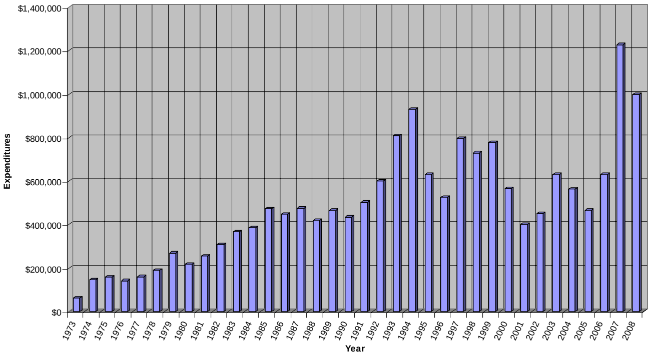
History – Membership Fees

Figure II - Membership Fee History



History - Expenditures

Figure III - History of TUFFP Expenditures



Membership Fees

- 2007 Membership Dues
  - 2 Unpaid
  - Expect to Be Paid Shortly
- 2008 Membership Dues
  - 9 of 17 Paid as of April 4
  - Need your prompt payments

Introduction

This semi-annual report is submitted to Tulsa University Fluid Flow Projects (TUFFP) members to summarize activities since the November 6, 2007 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 70th semi-annual Advisory Board meeting to be held at Allen Chapman Activity Center (ACAC) of the University of Tulsa South Campus, Tulsa Oklahoma on Thursday, April 15, 2008.

The activities will start with Tulsa University High Viscosity Projects (TUHOP) Advisory Board meeting on April 14, 2008 between 9:00 AM and noon. Between 1:00 and 3:00 PM on April 14, 2008, there will be TUFFP workshop. There will be four presentations made by four different TUFFP member companies. A facility tour will be held on April 14, 2007 between 3:00 and 5:00 p.m. Following the tour, there will be a social between 6:00 and 9:00 p.m. in Reynolds Center at President's Suite. The Advisory Board meeting will convene at 8:00 a.m. on April 15th and will adjourn at approximately 4:30 p.m. Following the meeting, there will be a joint TUFFP and TUPDP reception between 6:00 and 9:00 p.m. in Reynolds Center at President's Suite.

The Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board meeting will be held on April 16th at ACAC between 8:30 a.m. and 1:00 p.m.

The reception and the social function will provide an opportunity for informal discussions among members, guests, and TUFFP, TUPDP, and TUHOP staff and students.

Several TUFFP facilities will be operating during the tour. An opportunity will also be available to view the single-phase, multiphase, and small scale paraffin deposition test facilities and the hydrate flow loop.

The following dates have tentatively been established for fall 2008 Advisory Board meetings. The fall 2008 Advisory Board meetings will be held at ACAC.

2008 Fall Meetings

September 16, 2008	Tulsa University High Viscosity Oil Projects (TUHOP) JIP Meeting Tulsa University Hydrate Flow Performance (TUHFP) JIP Meeting Tulsa University Fluid Flow Projects (TUFFP) Workshop Facility Tour TUHOP – TUFFP Reception
September 17, 2008	Tulsa University Fluid Flow Projects (TUFFP) Advisory Board Meeting, TUFFP – TUPDP Reception
September 18, 2008	Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board Meeting

Personnel

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

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

Dr. Brill serves as a Research Professor of Petroleum Engineering on a part-time basis.

Dr. Abdel Salam Al-Sarkhi serves as the lead research associate for TUFFP. Abdel has received a Ph.D. in Mechanical Engineering from Oklahoma State University in 1999. Then, he spent two years as post-doctoral research associate at University of Illinois at Urbana-Champaign under Professor Thomas J. Hanratty. He has been a faculty member of Mechanical Engineering Department at Hashemite University in Jordan since fall 2001. He has conducted several research projects and published several peer reviewed papers on multiphase flow in pipes in respected Journals.

Dr. Mingxiu (Michelle) Li serves as a Research Associate for TUHOP, TUFFP, and related projects. Michelle received her Ph.D. from The University of Edinburgh in Bio-Fluid Dynamics – Department of Mechanical Engineering in March 2007. She has an M.Phil in Engineering Thermophysics from Department of Energy and Power Engineering of Xia'Tong University.

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

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

Mr. Brandon Kelsey serves as an electro-mechanical technician serving TUFFP, TUPDP, and TUHOP projects. Brandon is a graduate of OSU Okmulgee with a BS degree in instrumentation and automation degree.

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

Mr. James Miller, Computer Manager, and TUFFP TUPDP and TUHOP Web Administrator is currently on military leave. He is expected to return in November 2008.

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

Mr. Bahadir Gokcal continues his Ph.D. degree studies conducting research on High Viscosity Two-phase Flow research. He is concentrating his efforts on Slug Flow for High Viscosity Two-phase Flow. Bahadir received a BS degree in Petroleum and Natural Gas Engineering from Middle East Technical University and an MS degree in Petroleum Engineering from The University of Tulsa.

Mr. Kwonil Choi is pursuing his Ph.D degree in Petroleum Engineering. He received B.S. degree in Metallurgical Engineering from Federal University of Rio Grande do Sul in Brazil and M.S. degree in Petroleum Engineering from State University of Campinas (UNICAMP) in Brazil. Kwon Il has extensive industry experience mostly with Petrobras. He is fully supported by PETROBRAS. He is conducting a research project titled "Lagrangian-Eulerian Transient Two-phase Flow Model".

Mr. Xiao Feng, from Peoples Republic of China, received a BS degree in Petroleum Engineering from China University of Geosciences with a distinction of ranking first in his graduating class. Mr. Feng is studying Three-phase Low Liquid Loading Flow in Inclined Pipes.

Mrs. Gizem Ersoy Gokcal, from Turkey, started her Ph.D. degree studies. She is working on the project titled "Three-phase Gas-Oil-Water Flow in Hilly Terrain Pipelines". Gizem received a BS degree in Petroleum and Natural Gas Engineering from Middle East Technical University and an MS degree in Petroleum Engineering from The University of Tulsa.

Mr. Kyle Magrini, a US National, received a BS degree in Electrical Engineering from The University of Tulsa. Kyle is assigned the project titled "Liquid Entrainment in Annular Two-phase in Inclined Pipes".

Mr. Anoop Sharma, from India, has a BS degree in Chemical Engineering from National Institute of Technology Karnataka, India. He has also involved in research at other universities such as Indian Institute of Science, Banglore, India. He is studying to improve the two-phase oil-water flow closure relationships.

Ms. Tingting Yu graduated in 2007 from China University of Petroleum (East China), majored in Oil and Gas Storage and Transportation. Tingting is now a teaching assistant for the Petroleum Engineering Department. She is working on a project investigating multiphase flow in annulus.

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

Table 1

2008 Fall Research Assistant Status

Name	*Origin*	*Stipend*	*Tuition*	*Degree Pursued*	*TUFFP Project*	*Completion Date*
Kwon Il Choi	Brazil	No – Petrobras	No – Petrobras	Ph.D. – PE	Lagrangian-Eulerian Transient Two-Phase Flow Model	Spring 2009
Gizem Ersoy	Turkey	Yes – TUFFP	Yes – TUFFP	Ph.D. – PE	Multiphase Flow in Hilly Terrain Pipelines	Spring 2009
Xiao Feng	PRC	Yes – TUFFP	Yes – TUFFP	MS – PE	Three-Phase Gas-Oil-Water Low Liquid Loading Flow in Inclined Pipes	Fall 2008
Bahadir Gokcal	Turkey	Yes – TUFFP	Waived	Ph.D. – PE	High Viscosity Oil Multiphase Flow Behavior	Fall 2008
Kyle Magrini	USA	Yes – TUFFP	Yes – TUFFP	MS – PE	Entrainment Fraction in Annular Two-phase Flow in Inclined Pipes	Summer 2009
Anoop Sharma	India	Yes – TUFFP	Yes – TUFFP	MS – PE	Development of Oil-Water Flow Closure Relationships	Summer 2009
Tingting Yu	PRC	Partial – TUFFP	No – PE Depart.	MS – PE	Multiphase Flow in a Vertical Annulus	Summer 2009

Membership

The current membership of TUFFP stands at 16 industrial members and Mineral Management Services of Department of Interior (MMS).

Effective July 2003, DOE began supporting TUFFP in the development of new generation multiphase flow predictive tools for three-phase flow research. DOE's support translates into the equivalent four additional members for five years.

Landmark Graphics has terminated their membership for 2008.

Our efforts to increase the TUFFP membership level continues. BHP has shown an interest in joining TUFFP in 2008.

Table 2 lists all the current 2008 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.

Table 2

2008 Fluid Flow Projects Membership

Baker Atlas

BP Exploration

Chevron

ConocoPhillips

Exxon Mobil

JOGMEG

KOC

Marathon Oil Company

Minerals Management Service

PEMEX

Petrobras

Petronas

Rosneft

Schlumberger

Shell Global Solutions

Tenaris

Total

Equipment and Facilities Status

Test Facilities

The high viscosity two-phase flow loop is modified to conduct Taylor Bubble velocity experiments for inclined flow. The facility is equipped with laser sensor to measure the slug characteristics. Moreover, a visualization box is installed to get better high speed videos of the flow.

The three-phase facility is undergoing significant modifications to accommodate Three-phase Gas-oil-water Flow in Hilly Terrain Pipelines. A new test section with new instrumentation is designed and implemented.

The severe slugging facility is being modified for the Liquid Entrainment project. A new liquid film removal device was designed and constructed for a 2 in. pipe. The design is improved based on the tests conducted in a 2 in. pipe. The improved device is currently under construction.

The design of a high pressure (500 psi operating pressures) and large diameter (6 in. ID) facility is complete. Location of the facility is identified and site drawings are prepared. Major equipments with long lead time have already been ordered. The generator has already been delivered. Tulsa City Fire Marshall has been informed about the new facility. No serious issues have been raised by the Fire Marshall. The facility design is planned to be audited for safety aspects by an independent engineering company. After the audit, necessary design changes will be implemented. The final stage before construction will be the HAZOP exercise with the involvement of Chevron HAZOP engineers. Chevron has generously offered their help.

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

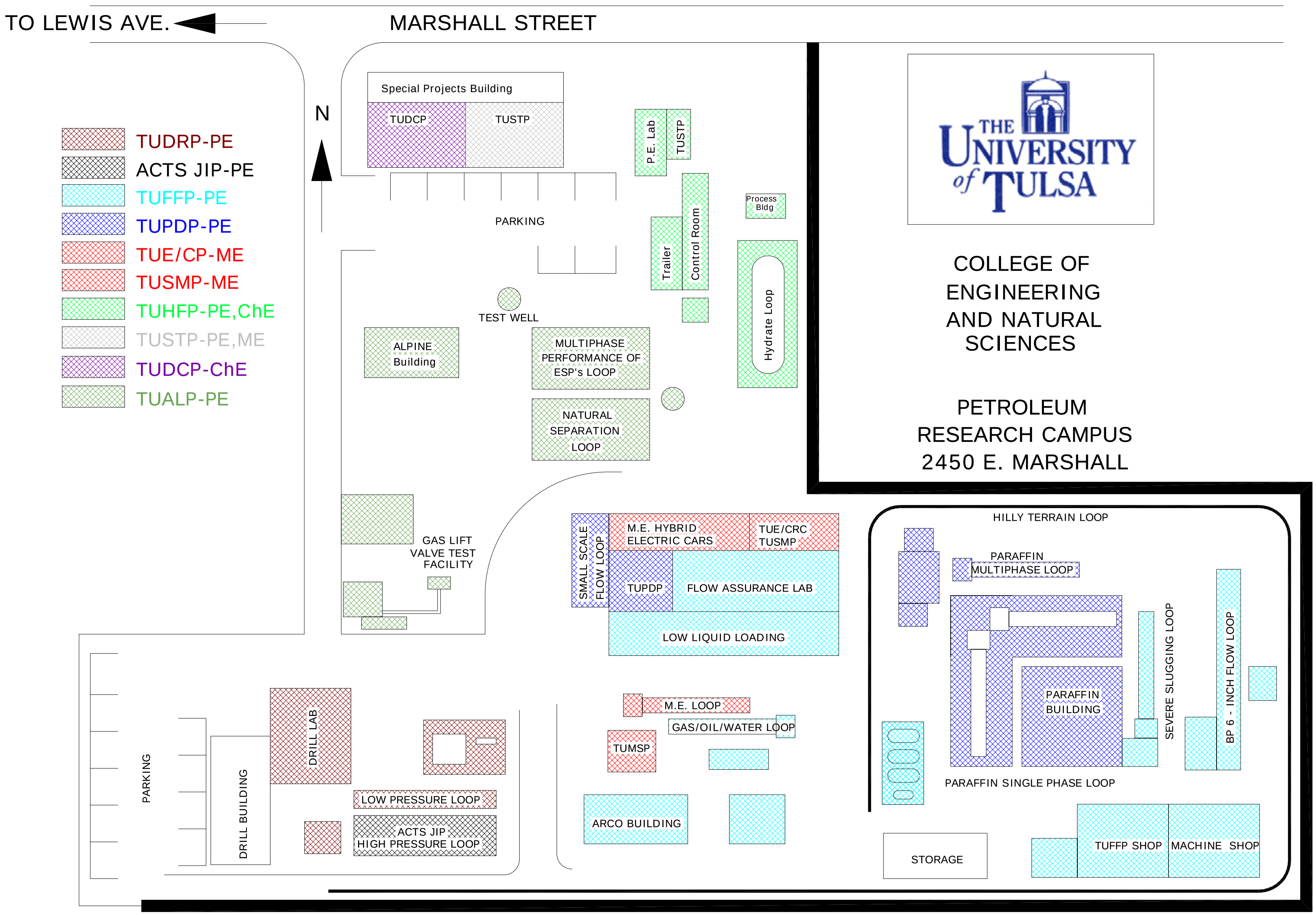


Figure 1 – Site Plan for the North Campus Research Facilities

Financial Status

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

As of April 8th, 2008, 16 of the 18 TUFFP members had paid their 2007 membership fees. The members who have not paid their membership fee were informed, and we expect expedited payments. Moreover, 8 of the 17 TUFFP members paid their 2008 membership fees. We appreciate your prompt payment of the membership dues.

Table 3 presents a financial analysis of income and expenditures for the 2007 Industrial member account as of December 31, 2007. This serves as unofficial closing budget for 2007. Also shown are previous 2007 budgets that have been reported to the members. The committed project industry income for 2007 was $680,000 based on 17 industrial members. The industry account reserve fund balance on December 31, 2006 was $644,242. The total industry account expenditures for 2007 are $712,137.54. The industry reserve account is $612,104.72 at the end of 2007.

Table 4 presents a financial analysis of expenditures and income for the MMS Account for 2007. This account is used primarily for graduate student stipends. A balance of $5,321.94 will be carried over to 2008.

Table 5 presents a financial analysis of expenditures and income for the DOE Account for 2007. The DOE Award is $731,995 over five years. The start date of the award was July 2003. A total of $129,480.39 is spent in 2007, leaving an award balance of $107,121.44 at the end of 2007.

The University of Tulsa waives up to 19 hours of tuition for each graduate student that is paid a stipend from the United States government, including both MMS and DOE funds. A total of 55 hours of tuition (equivalent of $38,000) was waived for 2007.

Tables 6-8 present the budgets and income for the Industrial, MMS, and DOE accounts for 2008. The 2008 TUFFP industrial membership fees will provide $758,000 of industrial membership income for 2008. The sum of the 2008 income and the reserve account is projected to be $1,370,104.72. The expenses for the industrial member account are estimated to be $1,211,412.70 leaving a balance of $158,692.02. The MMS account is expected to have a carryover of $509.14

Table 3: TUFFP 2007 Industrial Budget

2007 TUFFP Industrial Account Budget Summary

(Prepared April 8, 2008)

Anticipated Reserve Fund Balance on January 1, 2007		**644,242.26**
Income for 2007		
	2007 Membership Fees (15 @ $40,000 - excludes MMS)	**$600,000**
	2007 Membership Fees (1 @ 30,000)	**$30,000**
	2007 Membership Fees (1 @ 50,000)	**$50,000**
Total Budget		**1,324,242.26**

Projected Budget/Expenditures for 2007

		Budget	**Revised Budget 5/8/07**	**2007 Expenses**
90101 - 90110	Faculty Salaries	52,698.00	40,309.41	49,866.11
90600 - 90609	Professional Salaries	61,372.00	73,342.41	58,873.67
90700 - 90800	Technician	35,680.00	31,851.19	35,767.69
91000	Graduate Students - Monthly	50,100.00	50,100.00	46,769.84
91100	Students - Hourly	15,000.00	15,000.00	20,717.39
91800	Fringe Benefits (35%)	50,910.83	50,926.05	47,260.27
93100	General Supplies	3,000.00	3,000.00	4,629.09
93101	Research Supplies	100,000.00	100,000.00	82,998.83
93102	Copier/Printer Supplies	500.00	500.00	253.59
93104	Computer Software	4,000.00	4,000.00	1,801.79
93106	Office Supplies	2,000.00	2,000.00	1,343.24
93200	Postage/Shipping	500.00	500.00	1,491.06
93300	Printing/Duplicating	2,000.00	2,000.00	4,522.75
93400	Telecommunications	3,000.00	3,000.00	2,168.41
93500	Membership/Subscriptions	1,000.00	1,000.00	384.00
93600	Travel			153.81
93601	Travel - Domestic	14,000.00	14,000.00	6,622.77
93602	Travel - Foreign	10,000.00	10,000.00	4,768.83
93606	Visa		-	
93700	Entertainment (Advisory Board Meetings)	10,000.00	10,000.00	10,263.36
94803	Consultants		10,791.69	13,791.69
94813	Outside Services	20,000.00	20,000.00	9,652.55
95200	F&A (55.6%)	119,456.33	118,677.40	117,869.05
98900	Employee Recruiting	3,000.00	3,000.00	1,038.65
99001	Equipment	600,000.00	600,000.00	134,610.94
99002	Computers	8,000.00	8,000.00	19,190.13
99300	Bank Charges	40.00	40.00	18.00
81801	Tuition/Fees	30,306.00	30,306.00	34,377.00
81806	Graduate Fellowship			933.03
	Total Expenditures	**1,196,563.16**	**1,202,344.15**	**712,137.54**

Anticipated Reserve Fund Balance on December 31, 2007	**$ 612,104.72**

Table 4: TUFFP 2007 MMS Budget

2007 TUFFP MMS Budget Summary

(Prepared April 8, 2008)

Reserve Balance as of 12/31/06	**$6,110**
2007 Budget	**40,000**
Total Budget	**46,110**

Projected Budget/Expenditures for 2006

		Budget	**2007 Expenditures**	
91000	Students - Monthly	25,600.00	26,400.00	
95200	F&A	14,233.60	14,388.00	
81801	Tuition/Fees			
Total Anticipated Expenditures as of 12/31/07		**39,833.60**	**40,788.00**	
Total Anticipated Reserve Fund Balance as of 12/31/07				**5,321.94**

Table 5: TUFFP 2007 DOE Budget

2007 TUFFP DOE Budget

(PreparedApril 8, 2008)

Award Amount				**$731,995**
Amount Invoiced (June 1, 2003 - December 31, 2006)				**495,393.17**
Total Budget				**236,601.83**
Projected Budget/Expenditures for 2007				
		2007 Budget	**2007 Expenditures**	
90600	Professional Salary - Jones	8,281.00	8,250.40	
90601	Professional Salary - Wang/Abdel	15,228.00	13,201.39	
90602	Professional Salary - Graham	26,368.00	26,062.83	
90702	Technician - Mechanical	3,037.00	3,155.42	
91000	Graduate Students - Monthly	26,600.00	23,730.23	
91800	Fringe Benefits (35%)	18,520.00	17,135.99	
95200	F&A (51%)	40,454.71	37,944.14	
Total Anticipated Expenditures as of 12/31/07		**138,488.71**	**129,480.39**	
Anticipated Fund Balance on 12/31/07				**$ 107,121.44**

Table 6: 2008 Projected TUFFP Industrial Budget

2008 TUFFP Industrial Account Budget Summary

(Prepared April 8, 2008)

Anticipated Reserve Fund Balance on January 1, 2008		**612,104.72**
Income for 2008		
	2008 Membership Fees (15 @ $48,000 - excludes MMS)	**$720,000**
	2008 Membership Fees (1 @ 38,000)	**$38,000**
Total Budget		**1,370,104.72**

Projected Budget/Expenditures for 2008

		Proposed Budget	**Revised Budget 4/8/07**
90101 - 90110	Faculty Salaries	28,474.96	25,913.18
90600 - 90609	Professional Salaries	96,359.54	90,719.42
90700 - 90800	Technician - Miller	24,228.72	21,582.14
91000	Graduate Students - Monthly	65,000.00	65,000.00
91100	Students - Hourly	15,000.00	15,000.00
91800	Fringe Benefits (35%)	49,190.86	45,610.86
93100	General Supplies	3,000.00	3,000.00
93101	Research Supplies	100,000.00	100,000.00
93102	Copier/Printer Supplies	500.00	500.00
93104	Computer Software	4,000.00	4,000.00
93106	Office Supplies	2,000.00	2,000.00
93200	Postage/Shipping	500.00	500.00
93300	Printing/Duplicating	2,000.00	2,000.00
93400	Telecommunications	3,000.00	3,000.00
93500	Membership/Subscriptions	1,000.00	1,000.00
93600	Travel		
93601	Travel - Domestic	10,000.00	10,000.00
93602	Travel - Foreign	10,000.00	10,000.00
93606	Visa		-
93700	Entertainment (Advisory Board Meetings)	10,000.00	10,000.00
94803	Consultants	16,000.00	16,000.00
94813	Outside Services	20,000.00	100,000.00
95200	F&A (55.6%)	127,359.15	121,327.40
98901	Employee Recruiting	3,000.00	3,000.00
99001	Equipment	200,000.00	500,000.00
99002	Computers	8,000.00	8,000.00
99300	Bank Charges	40.00	40.00
81801	Tuition/Fees	53,219.70	53,219.70
81806	Graduate Fellowship		-
	Total Expenditures	**851,872.93**	**1,211,412.70**

Anticipated Reserve Fund Balance on December 31, 2008	**$ 158,692.02**

Table 7: TUFFP Projected 2008 MMS Budget

2008 TUFFP MMS Budget Summary

(April 8, 2008)

Reserve Balance as of 12/31/07			**$5,322**
2008 Budget			**40,000**
Total Budget			**45,322**
Projected Budget/Expenditures for 2008			
		Budget	
91000	Students - Monthly	28,800.00	
95200	F&A	16,012.80	
81801	Tuition/Fees		
Total Anticipated Expenditures as of 12/31/08		**44,812.80**	
Total Anticipated Reserve Fund Balance as of 12/31/08			**509.14**

Table 8: TUFFP Projected 2008 DOE Budget

2008 TUFFP DOE Budget

(Prepared April 8, 2008)

Award Amount			**$731,995**
Amount Invoiced (June 1, 2003 - December 31, 2007)			**624,873.56**
Total Budget			**107,121.44**
Projected Budget/Expenditures for 2008			
		2008 Budget	
90600	Professional Salary - Jones	6,279.00	
90601	Professional Salary - Wang/Abdel	22,958.33	
90602	Professional Salary - Graham	12,514.00	
90702	Technician - Mechanical	3,644.00	
90703	Technician - Mechanical	6,825.00	
91000	Graduate Students - Monthly	7,000.00	
91800	Fringe Benefits (33%)	17,232.50	
95200	F&A (51%)	30,202.50	
Total Anticipated Expenditures as of 5/31/08		**106,655.33**	
Anticipated Fund Balance on 5/31/08			**$ 466.11**

Miscellaneous Information

Fluid Flow Projects Short Course

The 33nd TUFFP "Two-Phase Flow in Pipes" short course offering is scheduled May 12-16, 2008. For this short course to be self sustaining, at least 10 enrollees are needed. We urge our TUFFP and TUPDP members to let us know soon if they plan to enroll people in the short course.

BHR Group Conference on Multiphase Technology

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

6th North American Conference on Multiphase Technology, supported by Neotechnology Consultants of Calgary, Canada, New Technology Magazine, SPT Group and TUFFP, is scheduled to be held 4-6 of June 2008 in Banff, Canada. The conference will benefit anyone engaged in the application, development and research of multiphase technology for the oil and gas industry. Applications in the oil and gas industry will also be of interest to engineers from other industries for which multiphase technology offers a novel solution to their problems. The conference will also be of particular value to designers, facility and operations engineers, consultants and researchers from operating, contracting, consultancy and technology companies. The conference brings together experts from across the American Continents and Worldwide.

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

Publications & Presentations

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

1. Keskin, C., Zhang, H. Q., and **Sarica, C.**: "Identification and Classification of New Three-Phase Gas/Oil/Water Flow Patterns," SPE 110221, Presented at SPE 2007 Annual Technical Conference and Exhibition, Anaheim, CA, Nov. 11-14, 2007.
2. Vielma, M., Atmaca, S., Zhang, H. Q., and **Sarica, C.**: "Characterization of Oil/Water Flows in Horizontal Pipes," SPE 109591, Presented at SPE 2007 Annual Technical Conference and Exhibition, Anaheim, CA, Nov. 11-14, 2007.
3. Al-Safran, E. **Sarica, C.** Zhang, H. Q., and Brill, J.P: "Mechanistic/Probabilistic Modeling of Slug Initiation in a Lower Elbow of a Hilly Terrain Pipeline," SPE 102254, *SPE Production & Operations Journal*, February 2008.

Paraffin Deposition Projects Activities

The third three year phase of TUPDP has been started. The studies concentrate on the paraffin deposition characterization of single-phase turbulent flow, oil-water paraffin deposition, gas-oil-water paraffin deposition.

TU CoRE Activities

The Center of Research Excellence (TUCoRE) initiated by Chevron at The University of Tulsa funds several research projects on flow assurance topics. TUFFP researchers are involved in various TUCoRE activities. One such activity is on High Viscosity Multiphase Flow (TUHOP). Chevron has provided TU to $380,000 for improvement of an existing high pressure multiphase flow facility. Moreover, this research is being leveraged by forming a Joint Industry Project. Current members of the JIP are BP, and Chevron. Petrobras is interested in becoming a member.

Two-Phase Flow Calendar

Several technical meetings, seminars, and short courses involving two-phase flow in pipes are scheduled for 2008. Table 9 lists meetings that would be of interest to TUFFP members.

Table 9

Meeting and Conference Calendar

2008

May 5 – 8	Offshore Technology Conference, Houston, Texas
May 11 – 16	Deepwater – The Way Forward, Phuket, Thailand
May 12 – 16	TUFFP Short Course
June 4 – 6 2008	BHRg's Multiphase Technology 2008, Banff, Canada.
August 10 – 14	8th International Symposium on Numerical Methods for Multiphase Flows – 2008 ASME Fluids Engineering Conference, Jacksonville, Florida
September 4-7	Offshore Europe, Aberdeen, Scotland
September 16	TUHOP Fall Advisory Board meeting, Tulsa, OK
September 16	TUHFP Fall Advisory Board meeting, Tulsa, OK
September 16	TUFFP Fall Workshop, Tulsa, OK
September 17	TUFFP Fall Advisory Board meeting, Tulsa, OK
September 18	TUPDP Fall Advisory Board meeting, Tulsa, OK
September 21 – 24	SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA
December 3 – 5	International Petroleum Technology Conference, Kuala Lumpur, Malaysia

Appendix A

Fluid Flow Projects Deliverables[1]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

63. "Prudhoe Bay Large Diameter Slug Flow Experiments and Data Base System" Users Manual, by S. L. Scott (July 1989).

64. "Two-Phase Slug Flow in Upward Inclined Pipes", by G. Zheng (Dec. 1989).

65. "Elimination of Severe Slugging in a Pipeline-Riser System," by F. E. Jansen (May 1990).

66. "A Mechanistic Model for Predicting Annulus Bottomhole Pressures for Zero Net Liquid Flow in Pumping Wells," by D. Papadimitriou (May 1990).

67. "Evaluation of Slug Flow Models in Horizontal Pipes," by C. A. Daza (May 1990).

68. "A Comprehensive Mechanistic Model for Two-Phase Flow in Pipelines," by J. J. Xiao (Aug. 1990).

69. "Two-Phase Flow in Low Velocity Hilly Terrain Pipelines," by C. Sarica (Aug. 1990).

70. “Two-Phase Slug Flow Splitting Phenomenon at a Regular Horizontal Side-Arm Tee,” by S. Arirachakaran (Dec. 1990)

71. "RECENT PUBLICATIONS" - A collection of articles based on previous TUFFP research reports that have been published or are under review for various technical journals (May 1991).

72. "Two-Phase Flow in Horizontal Wells," by M. Ihara (October 1991).

73. "Two-Phase Slug Flow in Hilly Terrain Pipelines," by G. Zheng (October 1991).

74. "Slug Flow Phenomena in Inclined Pipes," by I. Alves (October 1991).

75. "Transient Flow and Pigging Dynamics in Two-Phase Pipelines," by K. Minami (October 1991).

76. "Transient Drift Flux Model for Wellbores," by O. Metin Gokdemir (November 1992).

77. "Slug Flow in Extended Reach Directional Wells," by Héctor Felizola (November 1992).

78. "Two-Phase Flow Splitting at a Tee Junction with an Upward Inclined Side Arm," by Peter Ashton (November 1992).

79. "Two-Phase Flow Splitting at a Tee Junction with a Downward Inclined Branch Arm," by Viswanatha Raju Penmatcha (November 1992).

80. "Annular Flow in Extended Reach Directional Wells," by Rafael Jose Paz Gonzalez (May 1994).

81. "An Experimental Study of Downward Slug Flow in Inclined Pipes," by Philippe Roumazeilles (November 1994).

82. "An Analysis of Imposed Two-Phase Flow Transients in Horizontal Pipelines Part-1 Experimental Results," by Fabrice Vigneron (March 1995).

83. "Investigation of Single Phase Liquid Flow Behavior in a Single Perforation Horizontal Well," by Hong Yuan (March 1995).

84. “1995 Data Documentation User’s Manual”, (October 1995).

85. “Recent Publications” A collection of articles based on previous TUFFP research reports that have been published or are under review for various technical journals (February 1996).

86. “1995 Final Report - Transportation of Liquids in Multiphase Pipelines Under Low Liquid Loading Conditions”, Final report submitted to Penn State University for subcontract on GRI Project.

87. “A Unified Model for Stratified-Wavy Two-Phase Flow Splitting at a Reduced Tee Junction with an Inclined Branch Arm”, by Srinagesh K. Marti (February 1996).

88. “Oil-Water Flow Patterns in Horizontal Pipes”, by José Luis Trallero (February 1996).

89. “A Study of Intermittent Flow in Downward Inclined Pipes” by Jiede Yang (June 1996).

90. “Slug Characteristics for Two-Phase Horizontal Flow”, by Robert Marcano (November 1996).

91. “Oil-Water Flow in Vertical and Deviated Wells”, by José Gonzalo Flores (October 1997).

92. “1997 Data Documentation and Software User’s Manual”, by Avni S. Kaya, Gerad Gibson and Cem Sarica (November 1997).

93. “Investigation of Single Phase Liquid Flow Behavior in Horizontal Wells”, by Hong Yuan (March 1998).

94. “Comprehensive Mechanistic Modeling of Two-Phase Flow in Deviated Wells” by Avni Serdar Kaya (December 1998).

95. “Low Liquid Loading Gas-Liquid Two-Phase Flow in Near-Horizontal Pipes” by Weihong Meng (August 1999).

96. “An Experimental Study of Two-Phase Flow in a Hilly-Terrain Pipeline” by Eissa Mohammed Al-Safran (August 1999).

97. “Oil-Water Flow Patterns and Pressure Gradients in Slightly Inclined Pipes” by Banu Alkaya (May 2000).

98. “Slug Dissipation in Downward Flow – Final Report” by Hong-Quan Zhang, Jasmine Yuan and James P. Brill (October 2000).

99. “Unified Model for Gas-Liquid Pipe Flow – Model Development and Validation” by Hong-Quan Zhang (January 2002).

100. “A Comprehensive Mechanistic Heat Transfer Model for Two-Phase Flow with High-Pressure Flow Pattern Validation” Ph.D. Dissertation by Ryo Manabe (December 2001).

101. “Revised Heat Transfer Model for Two-Phase Flow” Final Report by Qian Wang (March 2003).

102. “An Experimental and Theoretical Investigation of Slug Flow Characteristics in the Valley of a Hilly-Terrain Pipeline” Ph.D. Dissertation by Eissa Mohammed Al-safran (May 2003).

103. “An Investigation of Low Liquid Loading Gas-Liquid Stratified Flow in Near-Horizontal Pipes” Ph.D. Dissertation by Yongqian Fan.

104. “Severe Slugging Prediction for Gas-Oil-Water Flow in Pipeline-Riser Systems,” M.S. Thesis by Carlos Andrés Beltrán Romero (2005)

105. “Droplet-Homophase Interaction Study (Development of an Entrainment Fraction Model) – Final Report,” Xianghui Chen (2005)

106. “Effects of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes” M.S. Thesis by Bahadir Gokcal (2005)

107. “Characterization of Oil-Water Flows in Horizontal Pipes” M.S. Thesis by Maria Andreina Vielma Paredes (2006)

108. “Characterization of Oil-Water Flows in Inclined Pipes” M.S. Thesis by Serdar Atmaca (2007).

109. “An Experimental Study of Low Liquid Loading Gas-Oil-Water Flow in Horizontal Pipes” M.S. Thesis by Hongkun Dong (2007).

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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 **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
27.	Petrobras	6 Aug. '74	T: for 2000 R: for 2005 **Current**

1975

28.	ELF Exploration Production (now as TotalFina Elf)	24 Jul. '74	T: 24 Feb. '76 Tr. from Aquitaine Co. of Canada 19 Mar. '81 T: 29 Jan. '87 R: 17 Dec. '91
29.	Cities Service Oil and Gas Corp.	21 Oct. '74	T: 25 Oct. '82 R: 27 Jun. '84 T: 22 Sep. '86

30.	Texas Eastern Transmission Corp.	19 Nov. '74	T: 23 Aug. '82
31.	Aquitaine Co. of Canada, Ltd.	12 Dec. '74	T: 6 Nov. '80
32.	Texas Gas Transmission Corp.	4 Mar. '75	T: 7 Dec. '89

1976

33.	Panhandle Eastern Pipe Line Co.	15 Oct. '75	T: 7 Aug. '85
34.	Phillips Petroleum Co.	10 May '76	T: Aug. 94 R: Mar 98 T: 2002

1977

35.	N. V. Nederlandse Gasunie	11 Aug. '76	T: 26 Aug. '85
36.	Columbia Gas System Service Corp.	6 Oct. '76	T: 15 Oct. '85
37.	Consumers Power Co.	11 Apr. '77	T: 14 Dec. '83
38.	ANR Pipeline Co.	13 Apr. '77	TR: from Michigan- Wisconsin Pipeline Co. in 1984 T: 26 Sep. '84
39.	Scientific Software-Intercomp	28 Apr. '77	TR: to Kaneb from Intercomp 16 Nov. '77 TR: to SSI in June '83 T: 23 Sep. '86
40.	Flopetrol/Johnston-Schlumberger	5 May '77	T: 8 Aug. '86

1978

41.	Norsk Hydro a.s	13 Dec. '77	T: 5 Nov. '82 R: 1 Aug. '84 T: 8 May ‘96
42.	Dresser Industries Inc.	7 Jun. '78	T: 5 Nov. '82

1979

43.	Sohio Petroleum Co.	17 Nov. '78	T: 1 Oct. '86
44.	Esso Standard Libya	27 Nov. '78	T: 2 Jun. '82
45.	Shell Internationale Petroleum MIJ B.V. (SIPM)	30 Jan. '79	T: Sept. 98 for 1999

1980

46.	Fluor Ocean Services, Inc.	23 Oct. '79	T: 16 Sep. '82
47.	Texaco	30 Apr. '80	T: 20 Sep. ’01 for 2002
48.	BG Technology (Advantica)	15 Sep. '80	T: 2003

1981

49.	Det Norske Veritas	15 Aug. '80	T: 16 Nov. '82

1982

50.	Arabian Oil Co. Ltd.	11 May '82	T: Oct.'01 for 2002
51.	Petro Canada	25 May '82	T:28 Oct. '86
52.	Chiyoda	3 Jun. '82	T: 4 Apr '94
53.	BP	7 Oct. '81	**Current**

1983

54.	Pertamina	10 Jan. '83	T: for 2000 R: March 2006

1984

55.	Nippon Kokan K. K.	28 Jun. '83	T: 5 Sept. '94
56.	Britoil	20 Sep. '83	T: 1 Oct. '88
57.	TransCanada Pipelines	17 Nov. '83	T:30 Sep. '85
58.	Natural Gas Pipeline Co. of America (Midcon Corp.)	13 Feb. '84	T:16 Sep. '87
59.	JGC Corp.	12 Mar. '84	T: 22 Aug. '94

1985

60.	STATOIL	23 Oct. '85	T:16 Mar. '89

1986

61.	JOGMEC (formerly Japan National Oil Corp.)	3 Oct. '86	T: 2003 R: 2007 **Current**

1988

62.	China National Oil and Gas Exploration and Development Corporation	29 Aug. '87	T:17 Jul. '89
63.	Kerr McGee Corp.	8 Jul. '88	T:17 Sept. '92

1989

64.	Simulation Sciences, Inc.	19 Dec. '88	T: for 2001

1991

65.	Advanced Multiphase Technology	7 Nov. '90	T:28 Dec. '92

66.	Petronas	1 Apr. ‘91	T: 02 Mar. 98 R: 1 Jan 2001 **Current**

1992

67.	Instituto Colombiano Del Petroleo	19 July ‘91	T: 3 Sep. ’01 for 2002
68.	Institut Francais Du Petrole	16 July. '91	T: 8 June 2000
69.	Oil & Natural Gas Commission of India	27 Feb. '92	T: Sept. 97 for 1998

1994

70.	Baker Jardine & Associates	Dec. ‘93	T: 22 Sept. ‘95 for 1996

1998

71.	Baker Atlas	Dec. 97	**Current**
72.	Minerals Management Service (Department of Interior’s)	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	**Current**

2006

78.	Tenaris		**Current**
79.	Shell Global		**Current**
80.	Kuwait Oil Company		**Current**

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

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