THE UNIVERSITY of TULSA

Department of Petroleum Engineering

Fluid Flow Projects

Sixty-Ninth Semi-Annual Advisory Board Meeting Brochure and Presentation Slide Copy

November 6, 2007

Tulsa University Fluid Flow Projects
Sixty-Ninth Semi-Annual Advisory Board Meeting Agenda
Tuesday, November 6, 2007

Monday
November 5, 2007

Tulsa University Fluid Flow Projects, Tulsa University Paraffin Deposition Projects, Tulsa University High Viscosity JIP and Tulsa University Hydrate Flow Performance JIP
Tour of Test Facilities
University of Tulsa North Campus
2450 East Marshall
Tulsa, Oklahoma
3:00 – 5:00 p.m.

Tulsa University Fluid Flow Projects, Tulsa University Paraffin Deposition Projects, Tulsa University High Viscosity JIP and Tulsa University Hydrate Flow Performance JIP
Reception
University of Tulsa – Allen Chapman Activity Center (ACAC)
President's Formal Lounge
440 South Gary Street
Tulsa, Oklahoma
6:00 – 9:00 p.m.

Tuesday
November 6, 2007

Tulsa University Fluid Flow Projects
Advisory Board Meeting
University of Tulsa – Allen Chapman Activity Center (ACAC) Gallery
440 South Gary Street
Tulsa, Oklahoma
8:00 a.m. – 5:30 p.m.

Tulsa University Fluid Flow Projects, Tulsa University Paraffin Deposition Projects and Tulsa University High Viscosity JIP
Reception
The University of Tulsa – Allen Chapman Activity Center (ACAC)
President's Formal Lounge
440 South Gary Street
Tulsa, Oklahoma
6:00 – 9:00 p.m.

Wednesday
November 7, 2007

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. – 1:00 p.m.

Tulsa University High Viscosity JIP
Advisory Board Meeting
University of Tulsa – Allen Chapman Activity Center (ACAC) Gallery
440 South Gary Street
Tulsa, Oklahoma
1:30 – 4:00 p.m.

Tulsa University Hydrate Flow Performance JIP
Reception
University of Tulsa – Allen Chapman Activity Center (ACAC)
President's Formal Lounge
440 South Gary Street
Tulsa, Oklahoma
5:30 – 9:00 p.m.

Thursday
November 8, 2007

Tulsa University Hydrate Flow Performance JIP
Advisory Board Meeting
The University of Tulsa – Allen Chapman Activity Center (ACAC)
President's Formal Lounge
440 South Gary Street
Tulsa, Oklahoma
8:00 a.m. – 2:00 p.m.

Tulsa University Fluid Flow Projects
Sixty-Eighth Semi-Annual Advisory Board Meeting Agenda
Tuesday, November 6, 2007

8:00 a.m.	**Breakfast** **Allen Chapman Activity Center - Gallery**	
8:30	**Introductory Remarks**	Cem Sarica
8:40	**CAPE OPEN**	Michel Pons, Co-Lan
9:00	**TUFFP Progress Reports**	
	Characterization of Oil-Water Flows in Inclined Pipes	Serdar Atmaca
	Lagrangian-Eulerian Transient Two-phase Flow Model	Kwon Il Choi
10:30	**Coffee Break**	
10:30	**TUFFP Progress Reports**	
	Low Liquid Loading Gas-Oil-Water Flow in Horizontal Pipes	Hongkun (Tom) Dong
	Low Liquid Loading Gas-Oil-Water Flow in Inclined Pipes	*Feng Xiao*
	New Dimensionless Parameters and a Power Law Correlation for Pressure Drop of Gas-Liquid Flows in Horizontal Pipelines	Abdel Al-Sarkhi
12:15 p.m.	**Lunch – President's Formal Lounge**	
1:30 p.m.	**TUFFP Progress Reports**	
	An Experimental and Theoretical Investigation of Slug Flow for High Oil Viscosity in Horizontal and Near-Horizontal Pipes	Bahadir Gokcal
	Multiphase Flow in Hilly Terrain Pipelines	Gizem Ersoy
2:45	**Coffee Break**	
3:00	**TUFFP Project Reports**	
	Review of Drop-Homophase Interaction Study (Effect of Pipe Inclination)	Abdel Al-Sarkhi
	Up-scaling Studies in Multiphase Flow	Abdel Al-Sarkhi
	Three-Phase Flow Unified Model Update	Holden Zhang
3:50	**Questionnaire**	Abdel Al-Sarkhi
4:00	**TUFFP Business Report**	Cem Sarica
4:15	**Open Discussion**	Cem Sarica
5:30	**Adjourn**	
6:00	**TUFFP/TUPDP Reception** **Allen Chapman Activity Center – President's Formal Lounge**	

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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 analysis. A three-phase model has already been developed. A Ph.D. student and an MS student have been assigned to work on this project to investigate the inclined and vertical pipe three-phase flows.

- *"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 against experimental data and improve the models through better closure relationships. High speed video and other instruments are utilized to gather detailed information such as drop size distribution as function of flow patterns.

  After Ms. Maria Vielma's study on horizontal oil-water flow, Mr. Serdar Atmaca has recently completed a study on oil-water flow for inclined pipes. Inclination angles of ±1°, ±2°, and -5° are investigated. Flow pattern, pressure gradient, holdup, droplet size measurements were made for various operational conditions. Droplet size distribution is found to be log-normal. Measured maximum, minimum and average droplet sizes are compared with the predictions from the existing correlations. The results indicate poor performance of the existing correlations

- *"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, 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 droplet formation, surface waves, bubble entrainment, slug mixing zone, and even three-phase stratified flow.

  Earlier study conducted by Gokcal at TUFFP showed that the performances of existing models are not sufficient for high viscosity oils. It was found that increasing oil viscosity had a significant effect on flow behaviors. Mostly, intermittent flow (slug and elongated bubble) was observed in his study. Based on his results, this study will initially focus on 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. During this period, drift velocity measurements for horizontal pipe configuration have been made. The drift velocity is found to decrease with increasing liquid viscosity.

- *"Droplet Homo-phase Interaction Study"*. In multiphase flows, there are many cases 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 distributed in various projects such as oil-water flow, high viscosity oil two-phase flow and low-liquid loading projects.

  In the past a sensitivity study of multiphase flow predictive models showed that, in stratified and annular flows, the variation of droplet entrainment fraction can significantly affect the predicted pressure gradient. Although better entrainment fraction correlations were proposed, it is identified that there is a need to experimentally investigate the entrainment fraction for inclined pipes. A new experimental study will be initiated using the severe slugging facility.

- *"Lagrangian-Eulerian Transient Two-Phase Model"*. This project was formerly titled as "Three-phase Redistribution in Sub-sea Flow Line – Riser Systems after Shut-in. The main motivation for this study comes from the need to mitigate hydrate formation following the cool-down of the fluids and high pressure surge during the shut-in. The study of the transient temperature variation along with the phase redistribution is critical for the design of the flow line-riser system as well as for the flow assurance during production cycle.

First, a two-phase transient model is formulated and solved. The model is capable of simulating not only the phase redistribution but also any other transients. The model is recently tested by comparing it with severe slugging experimental data. Moreover, the applicability of the model for the well shut-in is recently demonstrated. The next step in the research will be modeling of three-phase transients by following a similar approach.

- *"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 pressure loss along a pipeline. Moreover, existence of water can significantly contribute to the problem of corrosion and hydrate formation. Therefore, understanding of the flow characteristics of low liquid loading gas-oil-water flow is of great importance in transportation of wet gas.

  During this period the testing was completed for horizontal flow configuration. A large amount of data is collected on various flow parameters such as flow patterns, phase distribution, onset of droplet entrainment, entrainment fraction, and film velocity. The results reveal a new flow phenomenon.

- *"Multiphase Flow in Hilly Terrain Pipelines".* The three-phase flow in hilly terrain pipelines is a common occurrence in operations. The existence of water phase in the system poses many potential flow assurance and processing problems. Most of the problems will be directly related to the flow characteristics. Although the characteristics of two-phase gas-liquid flow have been investigated exclusively, 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, compare existing models and develop closure relationships and predictive models for three-phase flow of gas-oil-water in hilly-terrain pipelines.

  The facility modifications are planned and currently being implemented. New water and oil pumps have been purchased from Seepex with a significant discount. A new three-phase separator has been ordered from Natco. A spill prevention plan is prepared and being implemented. The remaining tasks include purchasing of the metering equipment, changing of feed lines with large diameter pipes to reduce the pressure losses prior to the test section, and instrumentation of the facility.

- *"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.

  During this period, a detailed drawing of the facility is prepared and the location of the facility is identified. The major equipment such as circulation compressor, heat exchanger, three-phase separator, liquid tanks and a generator have been sized and identified. Among those, the generator has been ordered.

- *"Unified Mechanistic Model".* TUFFP maintains, and continuously improves upon the TUFFP unified model. Our 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.

Since the last Advisory Board meeting, JOGMEC and ExxonMobil have joined TUFFP. Therefore, current TUFFP membership stands at 18 (17 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. DOE funding that has supported our research activities in oil-water-gas project is ending in 2008. This means a loss of about $145,000/year income. To be able to continue at the same capacity and pace, the membership fee will be increased to $48,000/year effective 2008.

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 expected 12 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

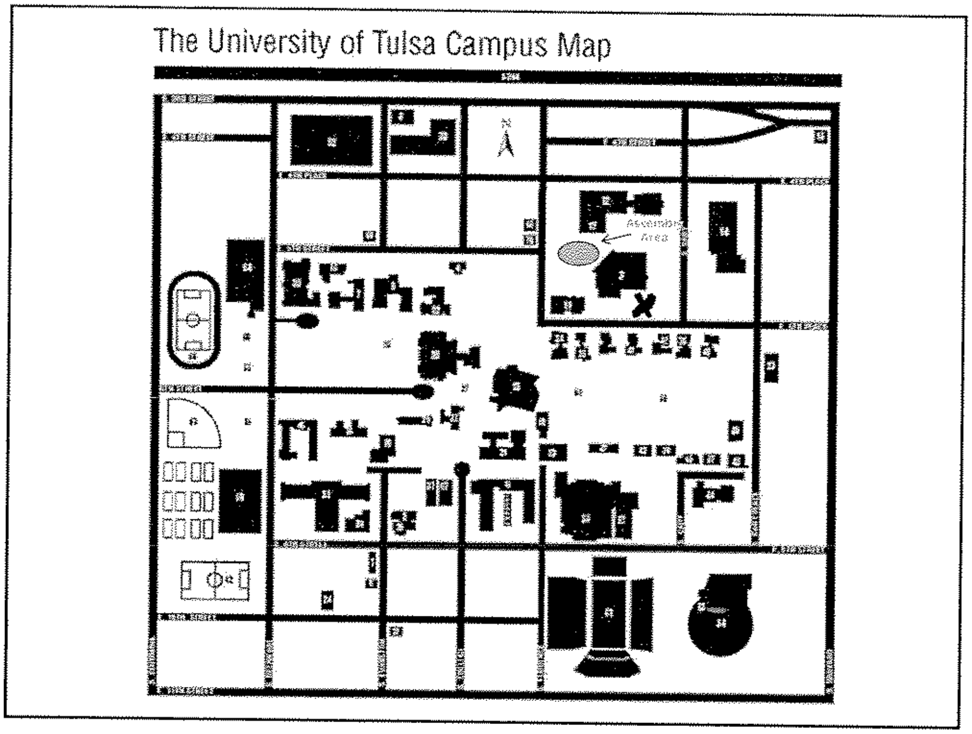
69th Fluid Flow Projects Advisory Board Meeting

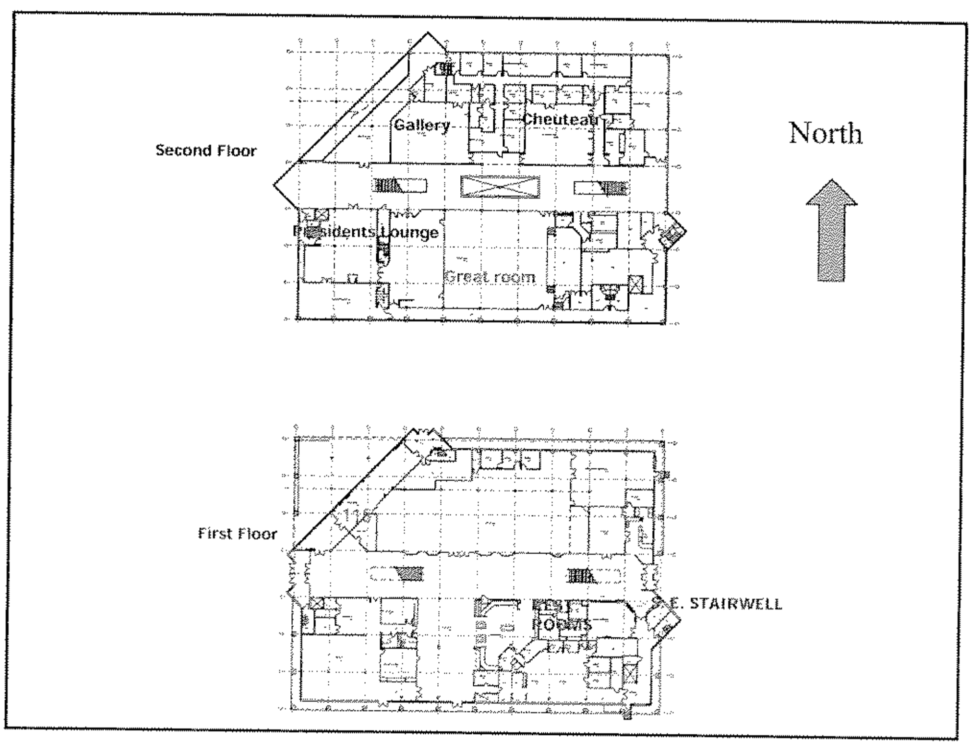
Welcome

Advisory Board Meeting, November 6, 2007

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
Assembly Area


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

Introductory Remarks

- 69th Semi-Annual Advisory Board Meeting
- Handout
  - Combined Brochure and Slide Copy
- Sign-Up List
  - Please Leave Business Card at Registration Table

Team

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

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

Team ...

- TUFFP Research Assistants
  - Serdar Atmaca (MS) – Turkey
  - Kwonil Choi (Ph.D.) – Brazil
  - Dongkun (Tom) Dong (MS) – PRC
  - 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
- Kamran Mirza, Seepex
- Michel Pons, CoLAN

Agenda

- 8:30 Introductory Remarks
- 8:40 CAPE OPEN
- 8:45 Progress Reports
  - An Experimental Study of Oil-Water Flows in Slightly Inclined Pipes
  - Lagrangian-Eulerian Transient Two-phase Flow Model
- 10:30 Coffee Break

Agenda ...

- 10:40 Progress Reports
  - Low Liquid Loading Gas-Oil-Water Flow in Horizontal Pipes
  - Low Liquid Loading Gas-Oil-Water Flow in Inclined Pipes
  - New Power Law Correlation for Pressure Drop of Gas-Liquid Flows
- 12:15 Lunch

  Allen Chapman Activity Center (ACAC) - Presidents Formal Lounge

Agenda ...

- 1:30 Progress Reports
  - Effect of High Oil Viscosity on Two-phase Oil-gas Flow Behavior
  - Multiphase Flow in Hilly Terrain Pipelines
- 2:45 Coffee Break

Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Agenda ...

- 3:00 Progress Reports ...
  - Droplet-Homophase Interaction Study
  - Up-scaling Studies
  - Three-phase Flow Unified Flow Update
- 3:50 Questionnaire
- 4:00 TUFFP Business Report
- 4:15 Open Discussion
- 4:30 Adjourn
- 6:00 TUFFP/TUPDP/TUHFP Reception (ACAC – President's Formal Lounge)

Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Fluid Flow Projects

Characterization of Oil-Water Flows in Inclined Pipes

Serdar Atmaca

Advisory Board Meeting, November 6, 2007

Outline

- Objectives
- Introduction
- Literature Review Summary
- Experimental Facility Modification
- Experimental Study
- Experimental Results
- Conclusions

Design improved pipelines / Facilities

Objectives

- Acquire Detailed Experimental Data Including Droplet Size Distributions and Velocity Fields in Inclined Pipes for Different Operating Conditions
- Develop New Closure Relationship for Phase Distribution
- Improve Existing Oil-Water Flow Models or Develop New Ones if Necessary

Introduction

- Knowledge of Oil-Water Flow Mixtures Helps
  - Develop Better Two-Phase Liquid-Liquid Models
  - Understand More Complex Gas-Oil-Water Flow
  - Design Pipelines and Facilities

Literature Review Summary

- Experimental Data mostly on Holdup and Pressure Drop
- Studies Mostly for Horizontal Configuration
- No Consensus on Flow Characterization for Partially Dispersed Flow Pattern
- Very Limited Experimental Data on Droplet Size and Distribution

Experimental Study

- Velocity Ranges
  - Superficial Oil Velocity
    - 0.03 – 1.75 m/s
  - Superficial Water Velocity
    - 0.03 – 1.75 m/s
- Inclination
  - Horizontal Flow and Slightly Inclined
    - 0°, $\pm1^{\circ}$, $\pm2^{\circ}$ and -5°

Uncertainty Analysis

Measurement	Random Uncertainty	Systematic Uncertainty	Degrees of Freedom	Overall Uncertainty (U_{95})
Pressure Drop (Pa/m)	0.00503	0.04677	Infinity	0.04784
v_{sw} (m/s)	0.00003	0.00005	Infinity	0.00008
v_{so} (m/s)	0.00003	0.00001	Infinity	0.00007
v_M (m/s)	0.00005	0.00005	Infinity	0.00011
H_w	0.00459	0.02294	Infinity	0.02470
C_W/H_w	0.00644	0.02359	Infinity	0.02688

Experimental Results

- 324 Data Points
- 0°, ±1°, ±2° and -5° Inclination Angles Covered
- 0° Used for Comparisons
- Upward and Downward Representative Inclinations will be Presented

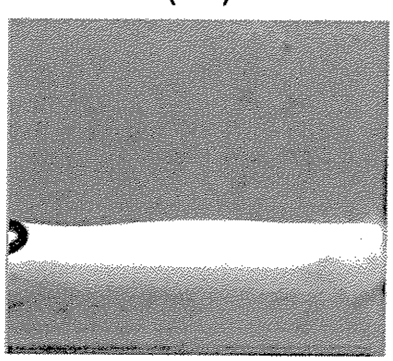
Experimental Results…

- Flow Patterns
- Pressure Gradients
- Water Holdup
- Phase Distributions
- Droplet Size and Distributions

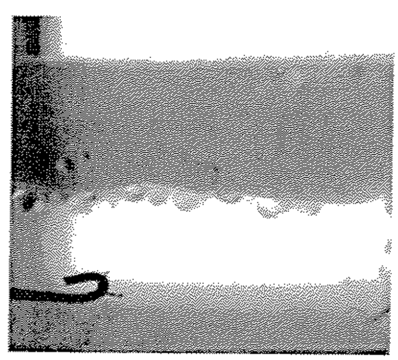
Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Flow Patterns

v_{SO}= 0.025 m/s
v_{SW}= 0.025 m/s
(ST)



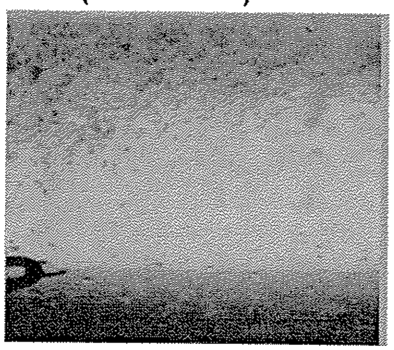
v_{SO}= 0.250 m/s
v_{SW}= 0.500 m/s
(ST&MI)



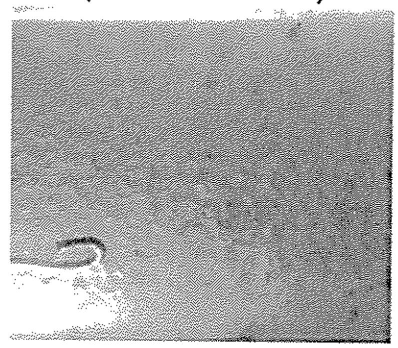
Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Flow Patterns...

v_{SO}= 0.050 m/s
v_{SW}= 1.000 m/s
(DO/W&W)



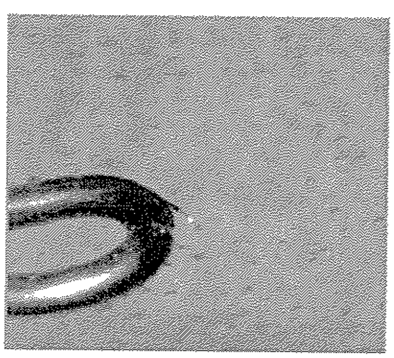
v_{SO}= 1.000 m/s
v_{SW}= 0.400 m/s
(DO/W &DW/O)



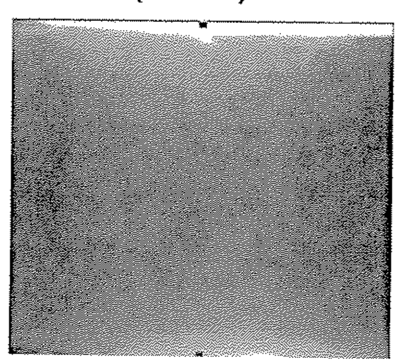
Fluid Flow Projects — Advisory Board Meeting, November 6, 2007

Flow Patterns...

v_{SO}= 0.050 m/s
v_{SW}= 1.750 m/s
(DO/W)



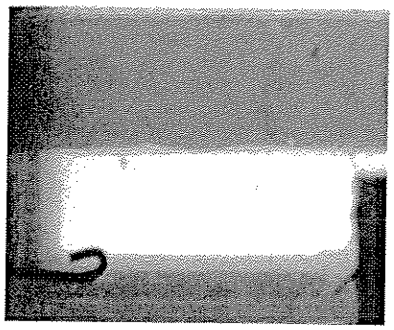
v_{SO}= 1.750 m/s
v_{SW}= 0.100 m/s
(DW/O)



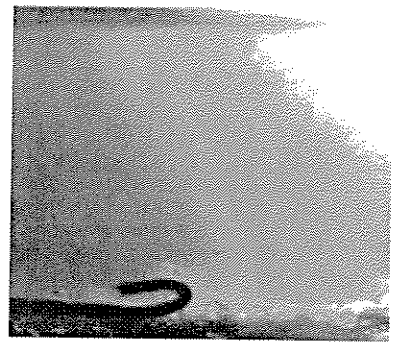
Fluid Flow Projects — Advisory Board Meeting, November 6, 2007

Flow Patterns…

v_{SO}= 0.100 m/s
v_{SW}= 0.250 m/s
(TRNS ST to ST&MI)



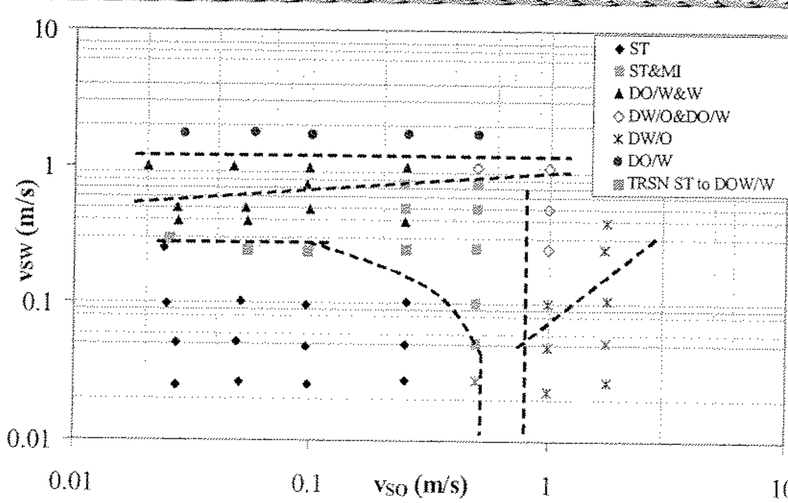
v_{SO}= 0.500 m/s
v_{SW}= 0.025 m/s
(DW/O&O)



Fluid Flow Projects

Advisory Board Meeting, November 6, 2007

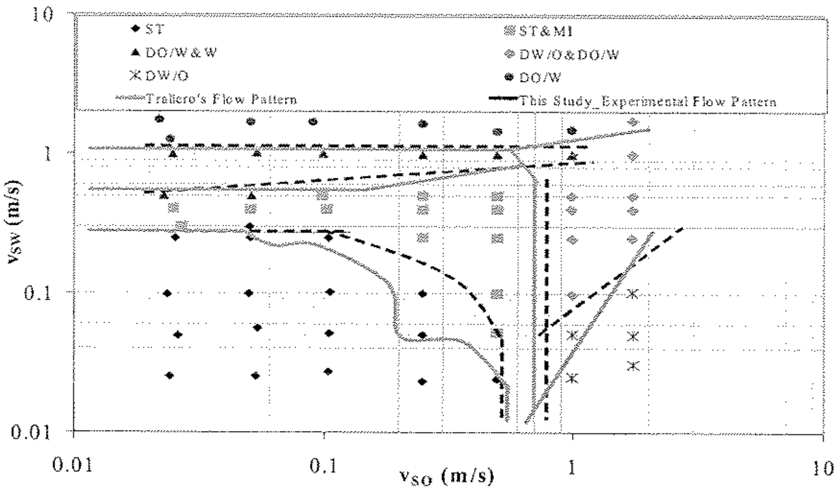
Experimental Flow Pattern Map
(θ=-1°)



Fluid Flow Projects

Advisory Board Meeting, November 6, 2007

Comparison of Flow Pattern Boundaries – Trallero (Horizontal)



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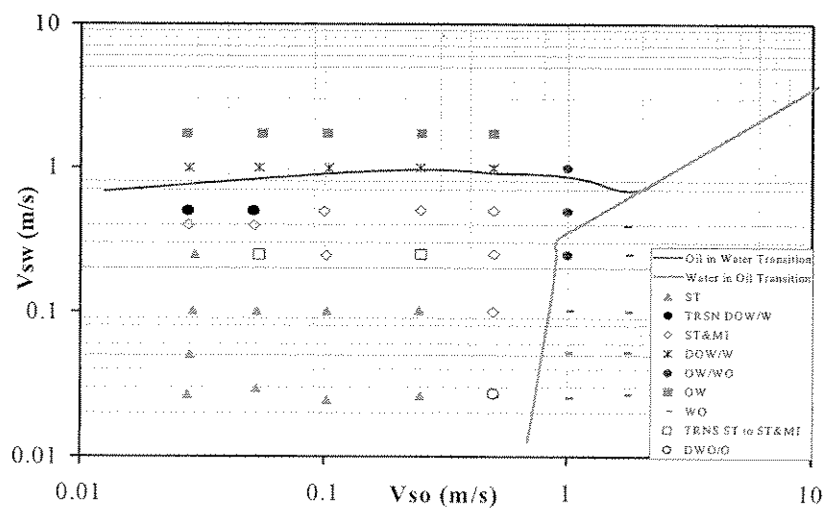
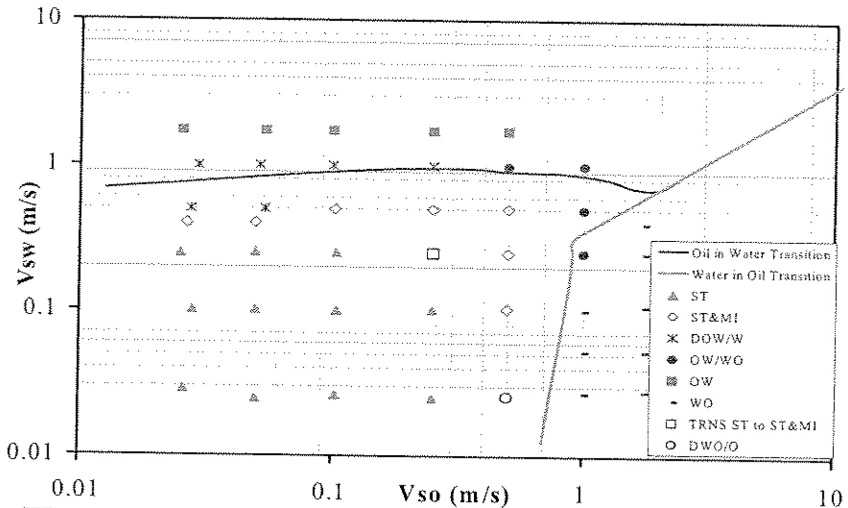
Comparison of Flow Pattern Boundaries Zhang et al. Model (θ=-2°)



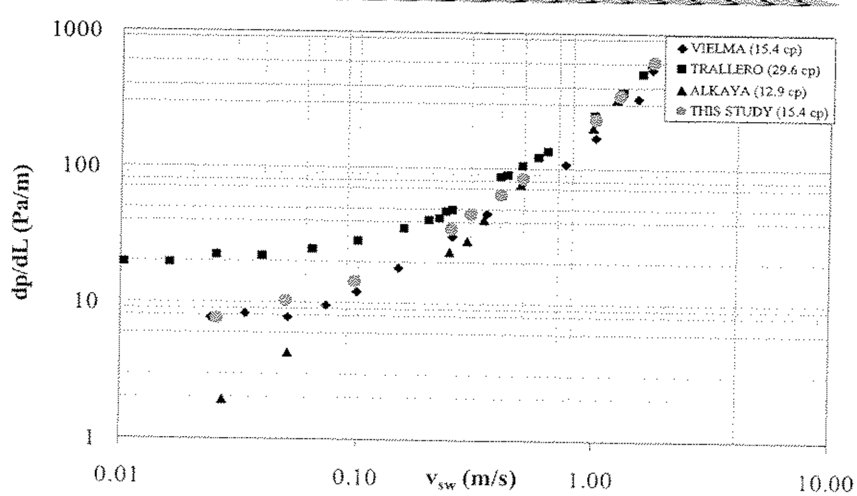
Fluid Flow Projects

Advisory Board Meeting, November 6, 2007

Comparison of Flow Pattern Boundaries Zhang et al. Model (θ=+2°)

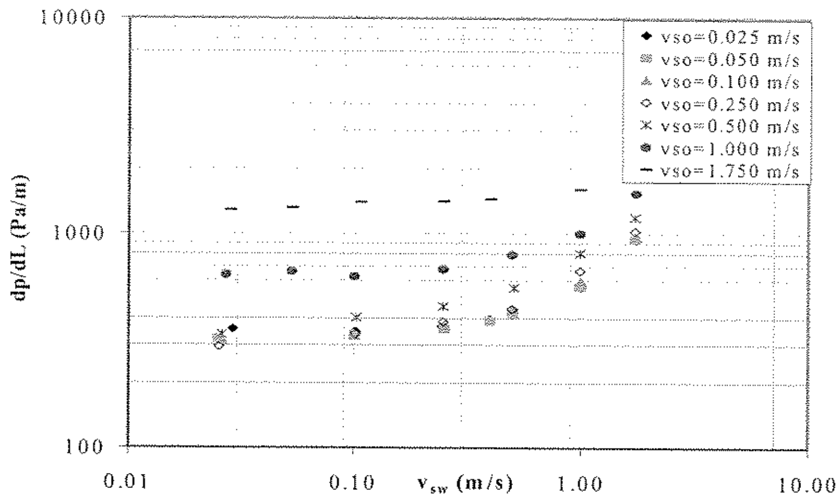


Pressure Gradients (v_{so}=0.025 m/s, Horizontal)



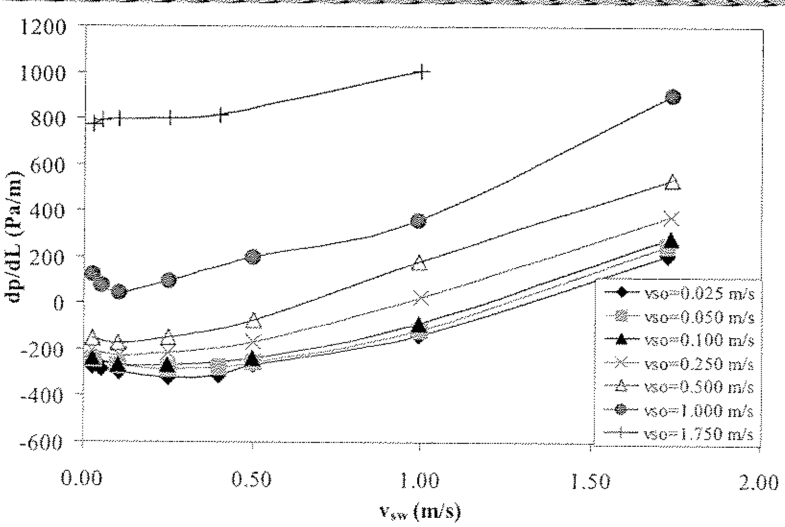
Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Experimental Pressure Gradients
(θ=+2°)

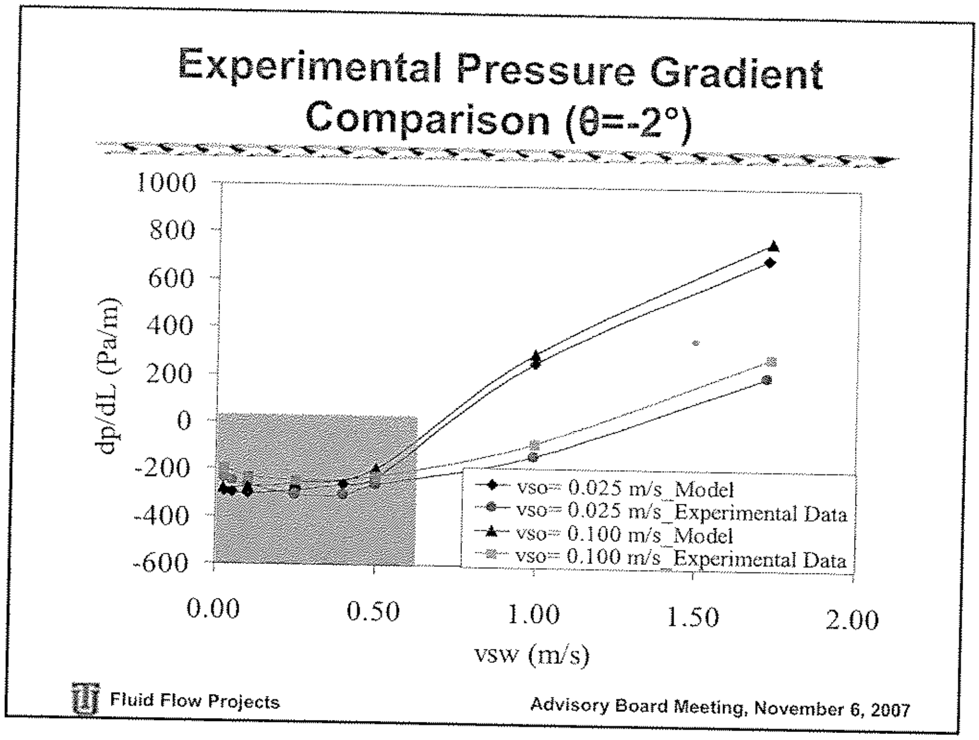


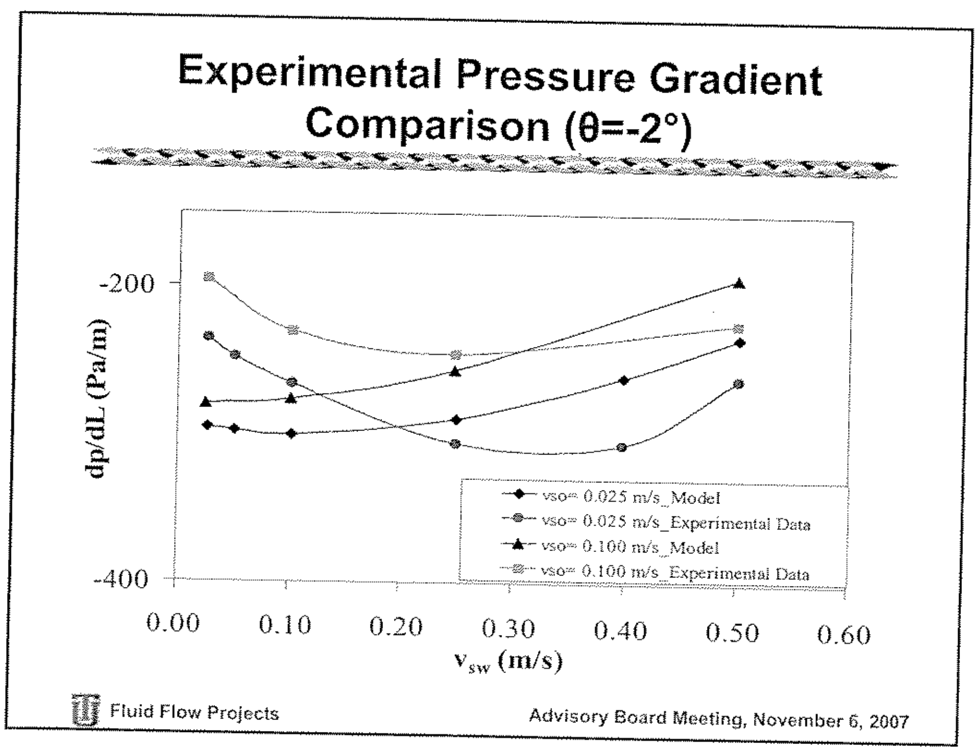
Fluid Flow Projects   Advisory Board Meeting, November 6, 2007

Experimental Pressure Gradients
(θ=-2°)



Fluid Flow Projects   Advisory Board Meeting, November 6, 2007


Experimental Pressure Gradient Comparison (θ=-2°)
1000
800
600
400
200
0
-200
-400
-600
dp/dL (Pa/m)
0.00
0.50
1.00
1.50
2.00
vsw (m/s)
vso= 0.025 m/s_Model
vso= 0.025 m/s_Experimental Data
vso= 0.100 m/s_Model
vso= 0.100 m/s_Experimental Data
Fluid Flow Projects
Advisory Board Meeting, November 6, 2007


Experimental Pressure Gradient Comparison (θ=-2°)
-200
-400
dp/dL (Pa/m)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
v_{sw} (m/s)
vso= 0.025 m/s_Model
vso= 0.025 m/s_Experimental Data
vso= 0.100 m/s_Model
vso= 0.100 m/s_Experimental Data
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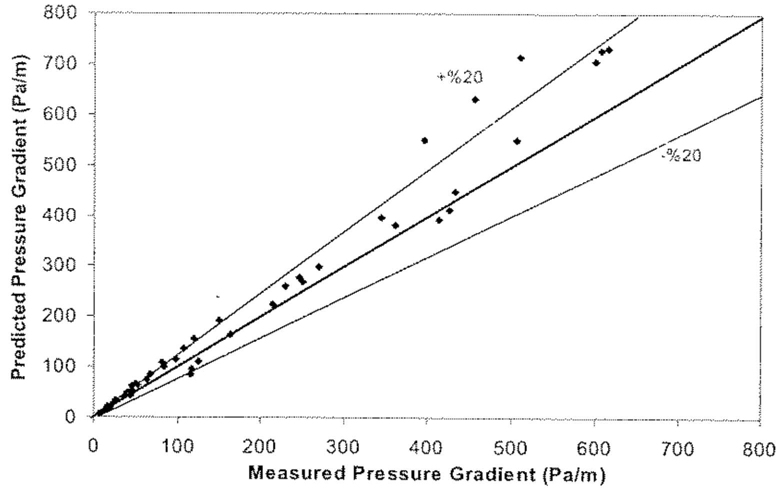
Comparison of Pressure Gradients Zhang et al. Model (Horizontal)



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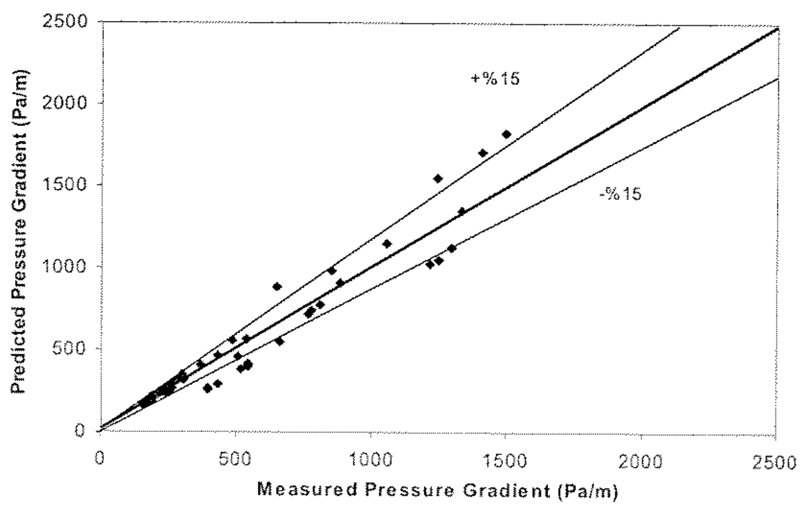
Comparison of Pressure Gradients Zhang et al. Model (θ=+1°)



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Pressure Gradient_Model Comparison (Unified Model)

	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (Pa/m)	ε_5 (Pa/m)	ε_6 (Pa/m)
Pressure Gradient	73.93	125.76	863.08	155.26	194.91	319.84

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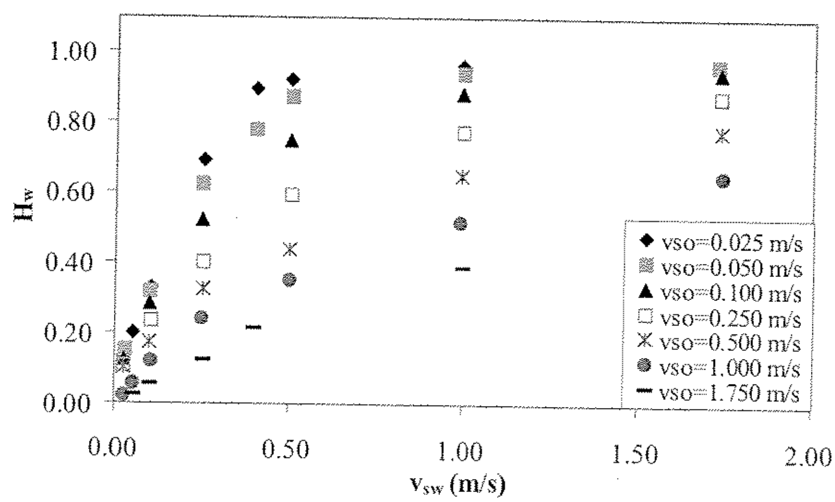
Experimental Water Holdup (θ=-2°)



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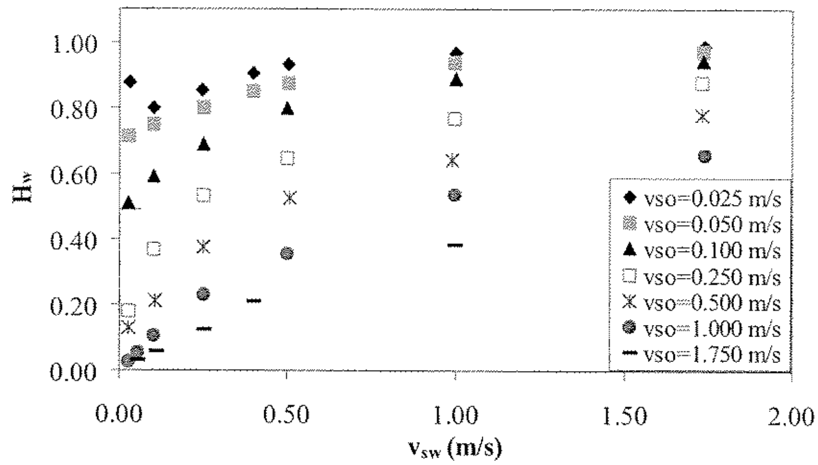
Experimental Water Holdup (θ=+2°)



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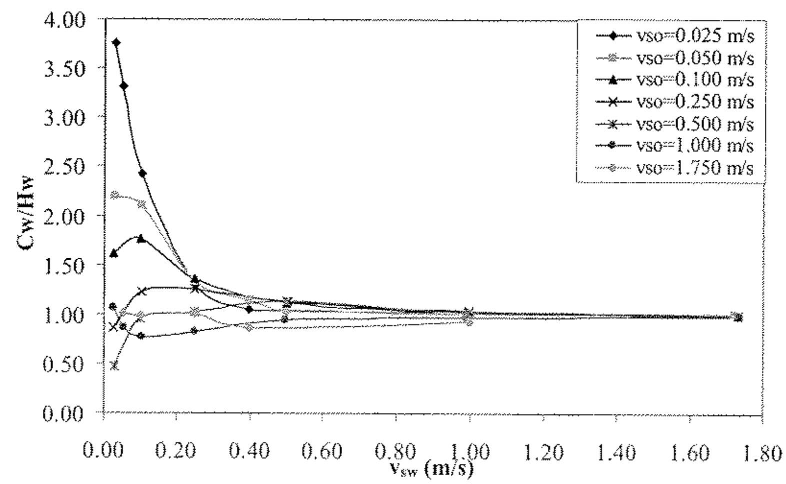
Experimental Water Holdup Ratio (θ=-2°)



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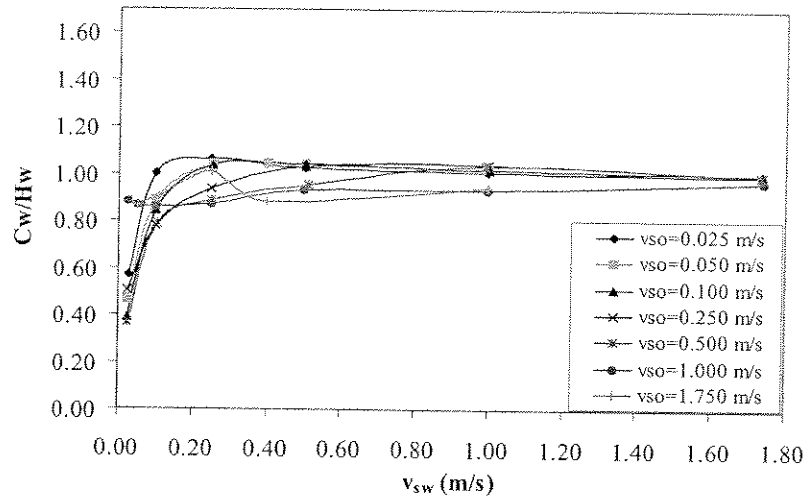
Experimental Water Holdup Ratio (θ=+2°)



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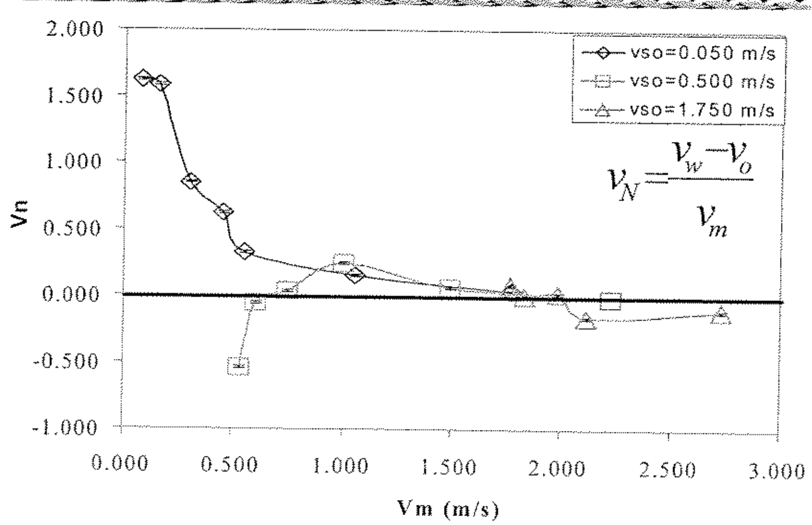
Normalized Drift Velocity (θ=-2°)



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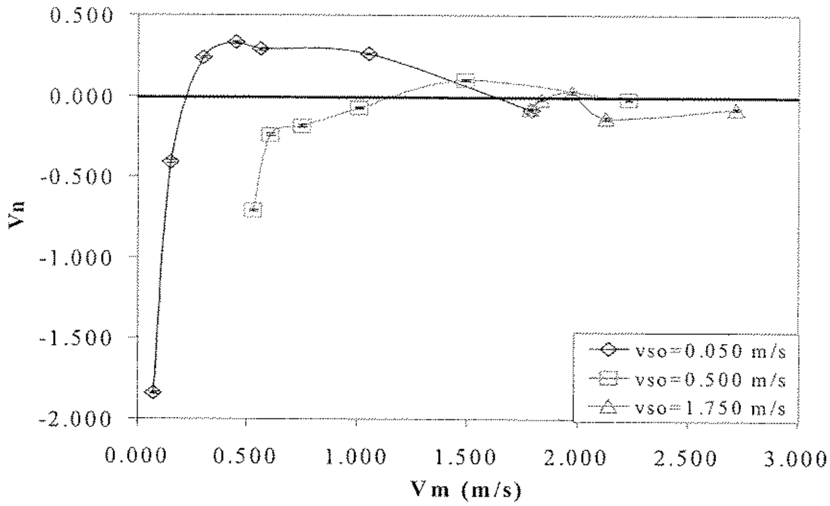
Normalized Drift Velocity (θ=+2°)



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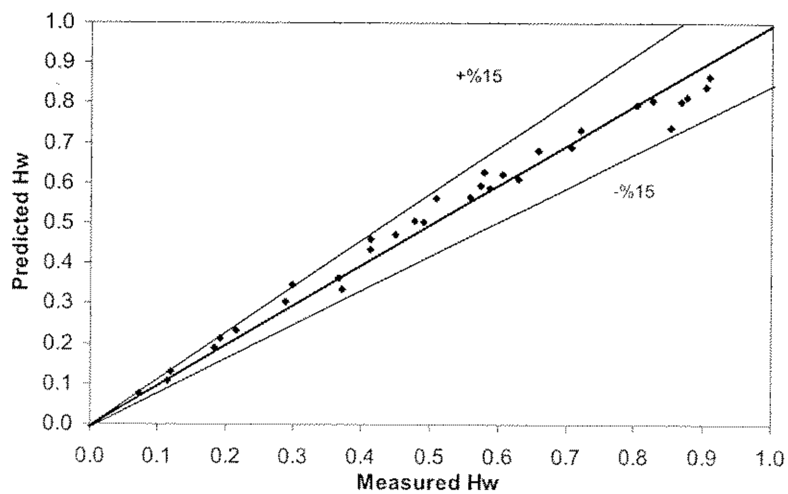
Comparison of Water Holdup Zhang et al. Model (θ=+1°)



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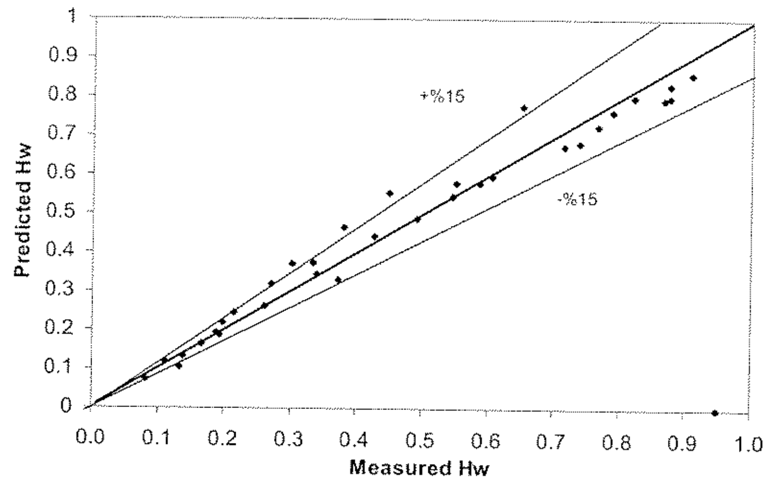
Comparison of Water Holdup Zhang et al. Model (θ=-1°)



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Water Holdup Model Comparison (Unified Model)

	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4	ε_5	ε_6
Water Holdup	1.43	9.65	27.23	0.01	0.04	0.04

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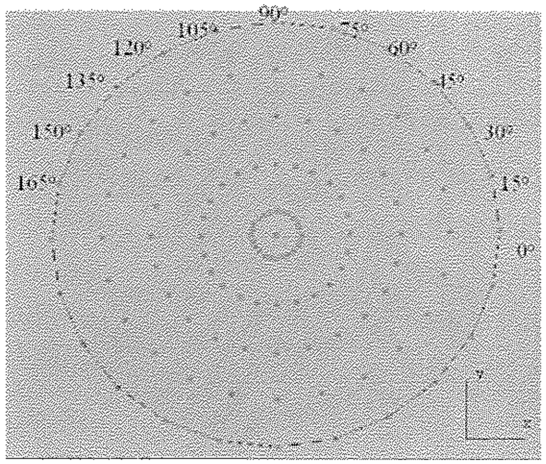
Phase Distribution



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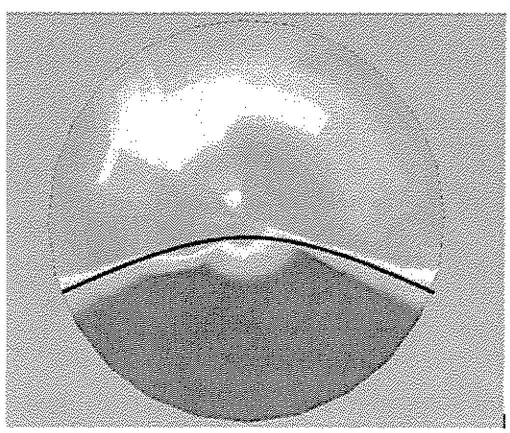
Phase Distribution...

v_{so}=0.050 m/s, v_{sw}=0.050 m/s, θ=-2°



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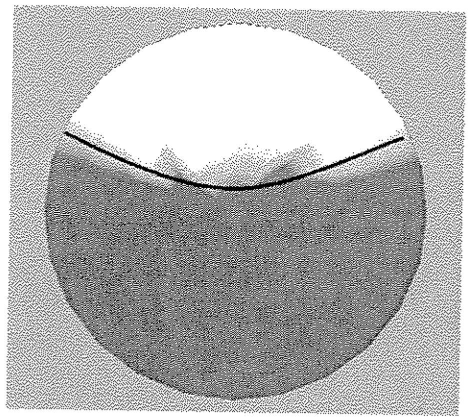
Phase Distribution...

v_{so}=0.050 m/s, v_{sw}=0.050 m/s, θ=+2°



Droplet Size Probabilistic Distributions

- SMD

$$SMD = \frac{\sum_{i=1}^{N} N_i \delta_i^3}{\sum_{i=1}^{N} N_i \delta_i^2}$$

- Normal

$$f(d) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2} * \left(\frac{d-\mu}{\sigma}\right)^2\right]$$

- Log-normal

$$f(d) = \frac{\exp\left(-\frac{1}{2}\left(\frac{\ln d - \mu}{\sigma}\right)^2\right)}{d * \sigma * 2\pi}$$

- Rosin-Rammler

$$F(d) = 1 - \exp\left(-\left(\frac{d}{\alpha}\right)^{\delta}\right)$$

Droplet Size
Probabilistic Distributions

- O/W
- W/O
- ST&MI
- DO/W&W
- DO/W&DW/O

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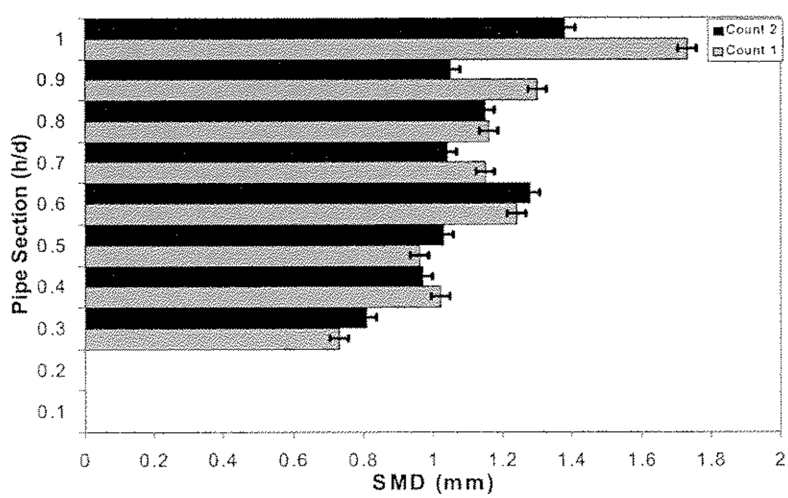
Droplet Size Distributions – Repeatability (v_{so}=0.050 m/s, v_{sw}=1.000 m/s, θ=0°)



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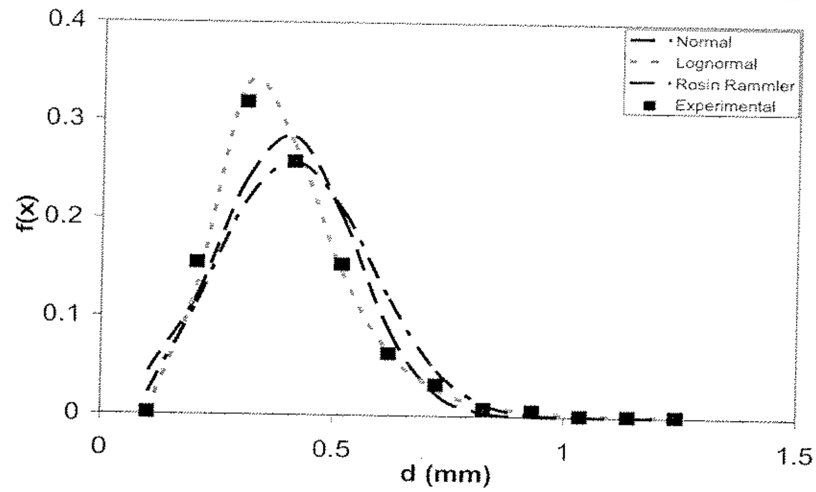
Droplet Size Distributions O/W (v_{so}=0.025 m/s, v_{sw}=1.750 m/s, θ=+2°)



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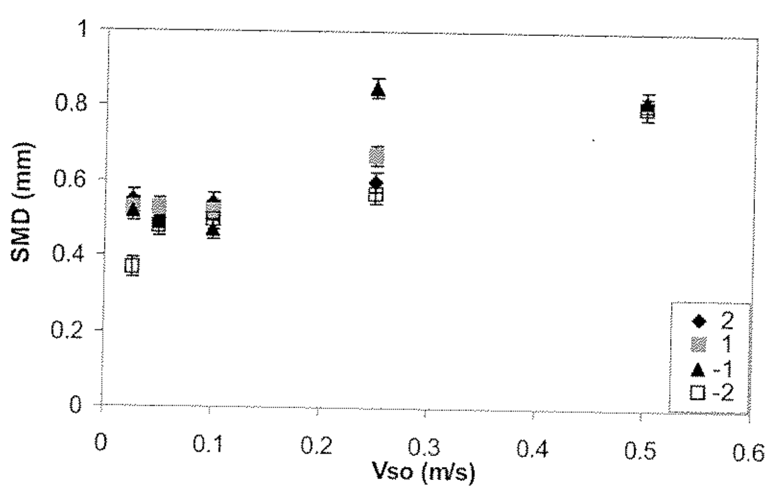
Variation of SMD with v_{so} and Inclination Angles for O/W Dispersions



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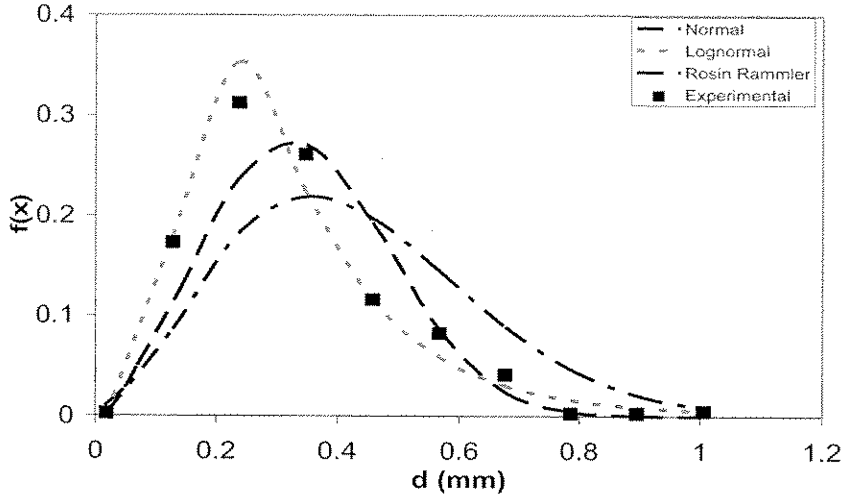
Droplet Size Distributions W/O
(v_{so}=1.750 m/s, v_{sw}=0.100 m/s, θ=+2°)



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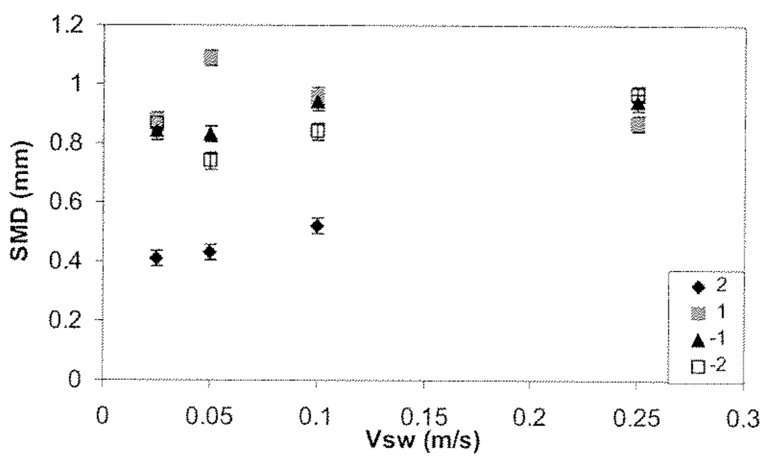
Variation of SMD with v_{sw} and Inclination Angles for W/O Dispersions



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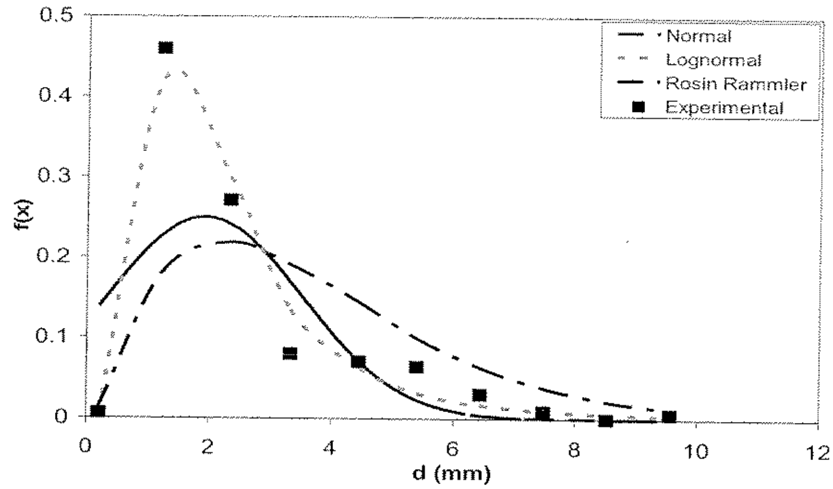
Droplet Size Distributions ST&MI (v_{so}=0.500 m/s, v_{sw}=0.100 m/s, θ=+2°)



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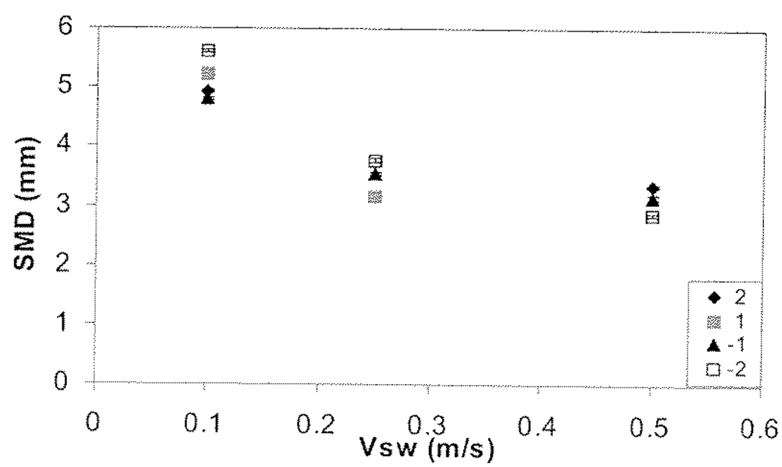
Variation of SMD with v_{sw} and Inclination Angles for ST&MI (v_{so}=0.500 m/s)



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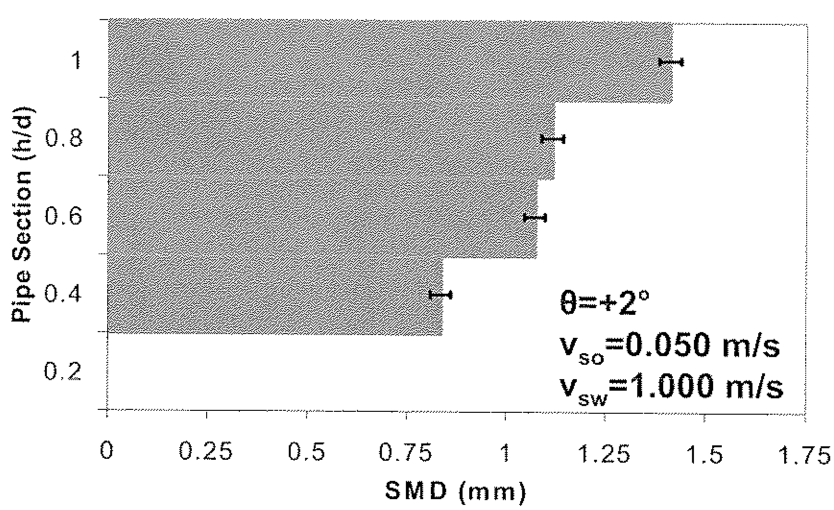
Variation of SMD with Pipe Section Inclination Angles for DO/W&W



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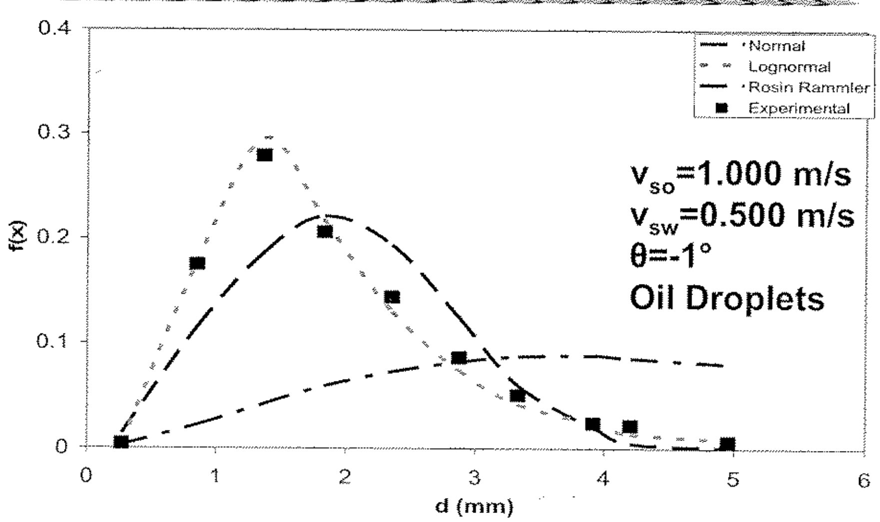
Droplet Size Distributions – DO/W&DW/O



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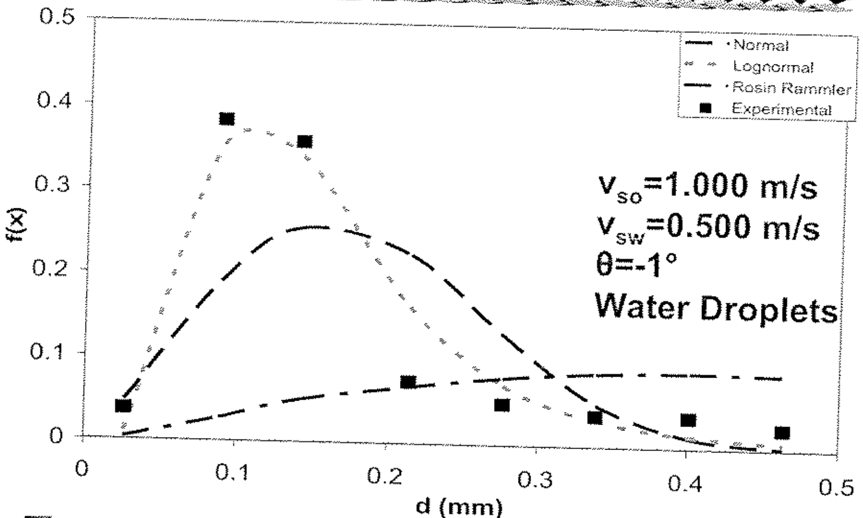
Droplet Size Distributions – DO/W&DW/O



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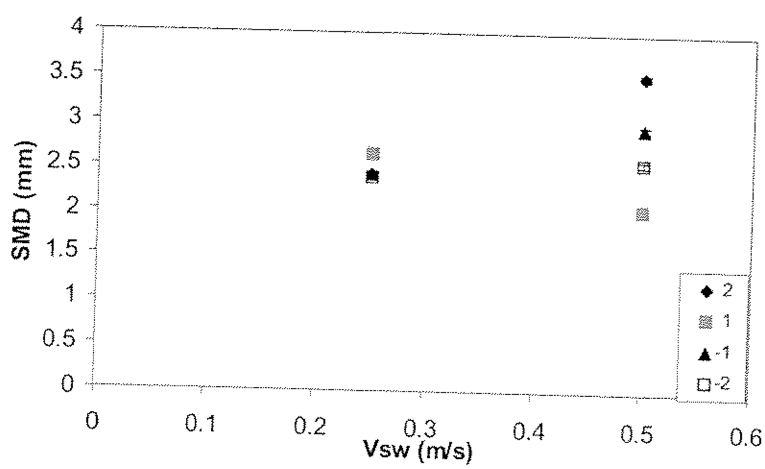
Variation of SMD with v_{sw} and Inclination Angles for Oil Droplets



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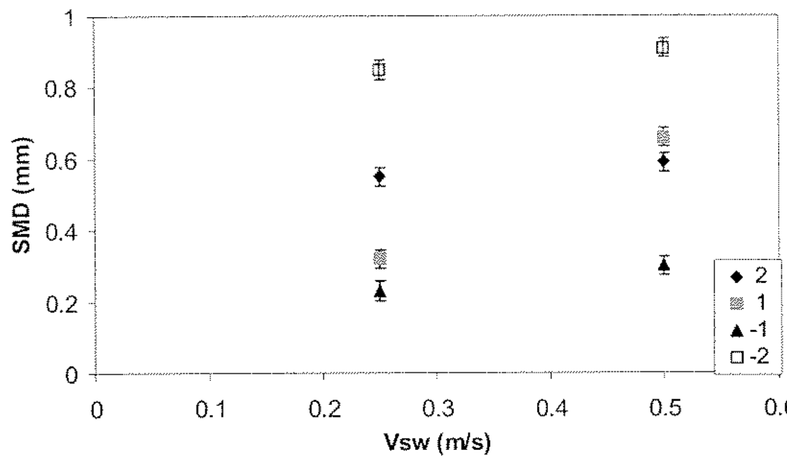
Variation of SMD with v_{sw} and Inclination Angles for Water Droplets



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Droplet Size Comparisons with Models

- Kouba (Maximum and Minimum)
- Brauner (Maximum for Both Dilute and Dense Dispersions)
- Angeli & Hewitt (Maximum and SMD)
- Kubie & Gardner (Maximum)
- Hinze (Maximum)

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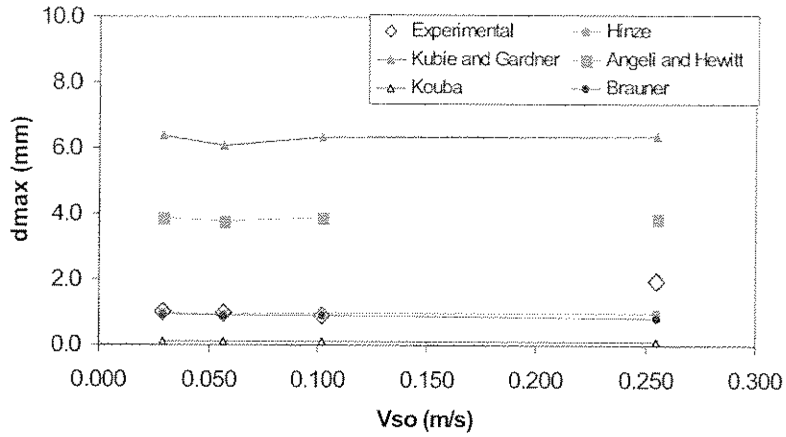
Maximum Droplet Size Comparisons O/W Dispersions

v_{sw}=1.750 m/s, θ=-1°



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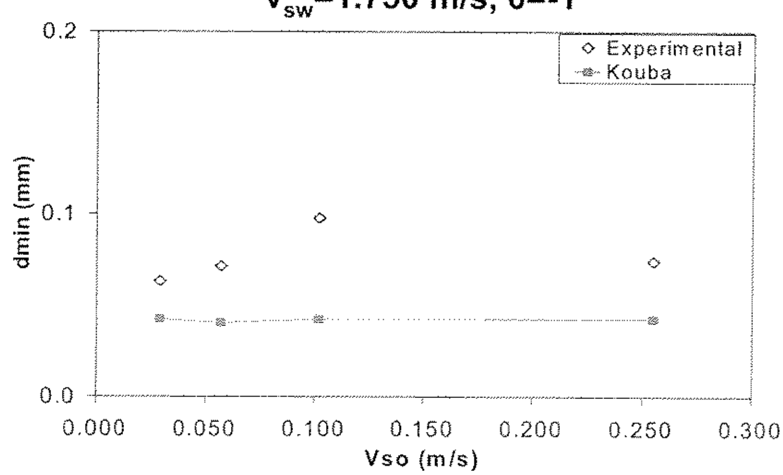
Minimum Droplet Size Comparisons O/W Dispersions

v_{sw}=1.750 m/s, θ=-1°



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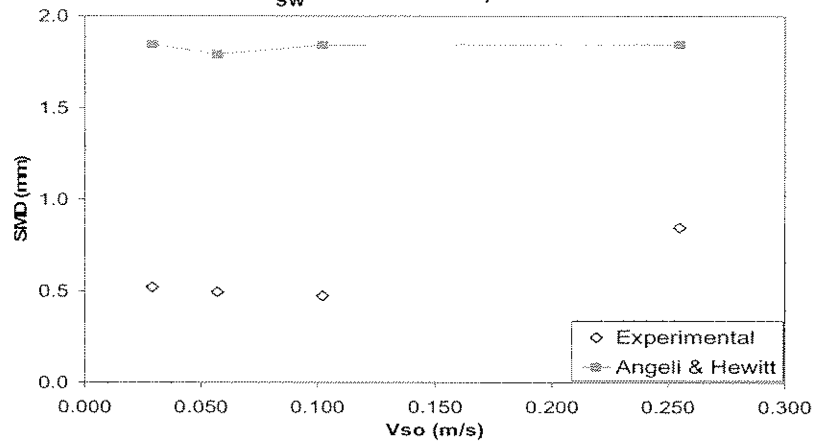
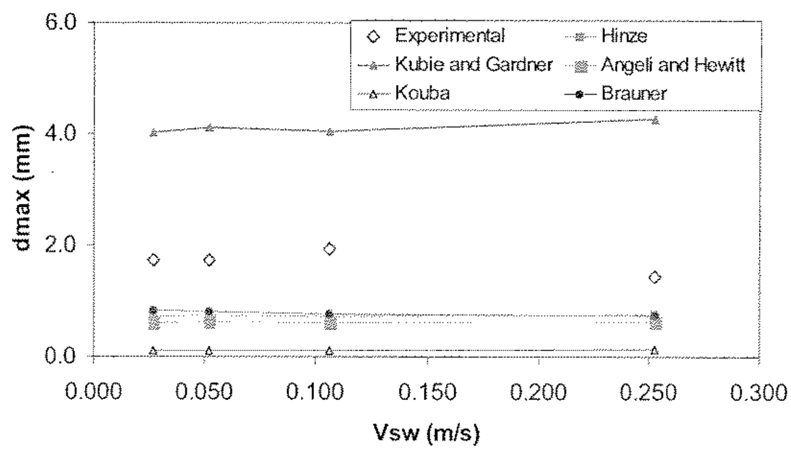
SMD Comparisons
O/W Dispersions

v_{sw}=1.750 m/s, θ=-1°



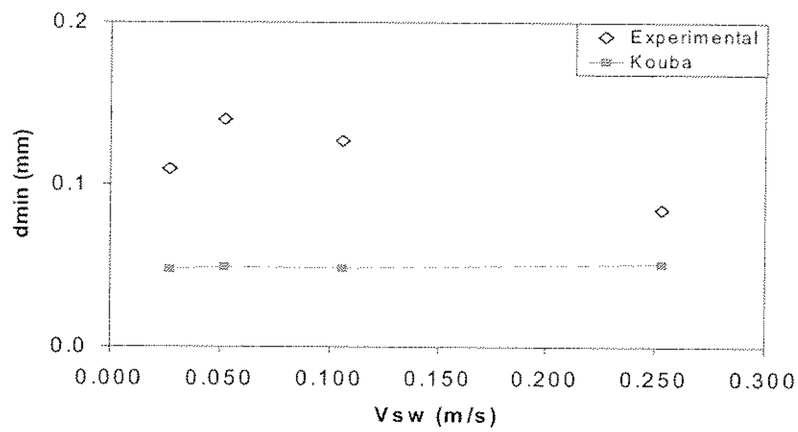
Maximum Droplet Size Comparisons
W/O Dispersions

v_{so}=1.750 m/s θ=-1°



Minimum Droplet Size Comparisons W/O Dispersions

v_{so}=1.750 m/s θ=-1°



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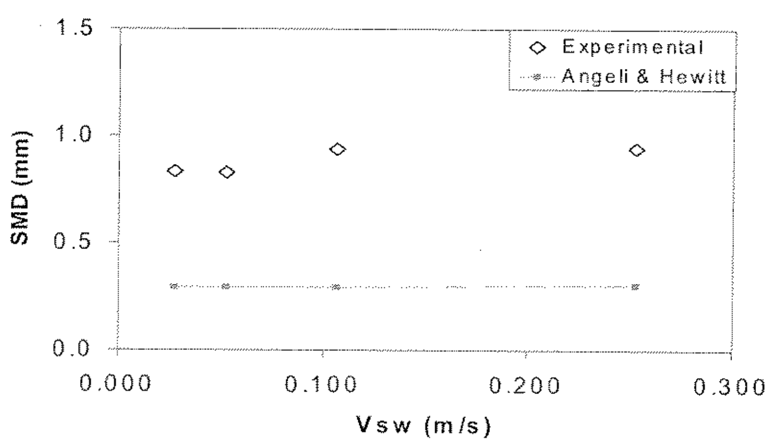
SMD Comparisons W/O Dispersions

v_{so}=1.750 m/s θ=-1°



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Droplet Size Model Comparisons

- Absolute Average Percentage Errors

d_{max} (O/W)	Hinze	19.00%
d_{max} (W/O)	Brauner	41.46%
d_{min} (O/W)	Kouba	43.49%
d_{min} (W/O)	Kouba	57.55%
SMD (O/W)	Angeli&Hewitt	199.32%
SMD (W/O)	Angeli&Hewitt	61.74%

Conclusions

- Flow Patterns
  - ST, ST&MI, DO/W&W, DO/W, DW/O, DO/W & DW/O, TRNS ST to ST&MI and DW/O&O Observed
  - Trallero Model Under-predicted ST Region
  - Zhang et al. Model Under-predicted DO/W Boundary

Conclusions …

- Pressure Gradient
  - Increases with Increasing v_{sw} and v_{so}
  - Existence of Minimum Pressure Gradient for in Downward Flow
  - Zhang et al.
    - Predicts Well in ST and ST&MI
    - Over-predicts DO/W

Conclusions …

- Water Holdup
  - Increases with Increasing v_{sw} and Decreases with Increasing v_{so}
  - $v_N > 0$ For Low/Medium Flow Rates for Downward Flow
  - $v_N < 0$ For Low/Medium Flow Rates for Upward Flow
  - Zhang et al. Predicts Water Holdup within 15% Error Band

Conclusions ...

- Droplet Size Distribution
  - Log-normal for All Flow Patterns
  - Increasing Trend in SMD for O/W and W/O with Increasing v_{so} and v_{sw}
  - Decreasing Trend in SMD for ST&MI
  - SMD has Increasing Trend from Bottom to Top for DO/W&W
  - No Clear Trend Observed for Inclination Angles

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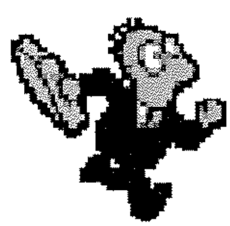
Questions & Comments



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Characterization of Oil Water Flow in Inclined Pipes

Serdar Atmaca

PROJECTED COMPLETION DATES:

Literature Review	Completed
Facility Modification	Completed
Testing	Completed
Model Comparison and Development	Completed
Final Report	Completed

Objectives

The main objective of this study is to investigate the oil-water flow behavior in inclined pipes and collect experimental data on oil-water flow including droplet sizes, pressure drop, liquid holdup, phase distribution and velocity fields to understand the physics and phenomena of oil-water flow. The existing models will be tested against the data, and attempts will be made to improve the existing models or develop new ones if necessary.

Introduction

Two-phase liquid pipe flow is defined as the simultaneous flow of two immiscible liquids in pipes. One of the common occurrences in the petroleum industry during transportation and production is oil-water flow in pipes. Moreover, two-phase liquid-liquid flow is common in process and petrochemical industry. Perhaps the most relevant and important application is transportation of oil-water through pipelines. Although the accurate prediction of oil-water flow is essential, oil-water flow in pipes have not been explored as much as gas-liquid flow as seen from a detailed literature review that can be found in April 2007 ABM report.

In this study, 324 data points were collected and used in the analysis of pressure gradient, water holdup, phase distribution and droplet size distribution. In the literature, there is limited data for inclined flow especially for the droplet size and its distribution and phase distribution. All the results are compared against the available models to check the performances of the models.

Experimental Study

The gas-oil-water facility is used for the experimental part of this study. The TUFFP gas-oil-water flow facility has been used for different studies by Vielma (2007), Keskin (2007), Alkaya (2000), Flores (1997) and Trallero (1995). In these studies horizontal, inclined, deviated and vertical oil-water and gas-oil-water experiments were conducted.

Experimental Facility and Flow Loop

The facility (as shown in Fig. 1) consists of a closed flow loop with the following components: pumps, heat exchangers, metering sections, filters, test section, separator and storage tanks. The test section is attached to and inclinable boom. Aluminum nets cover around the entire pipes to protect against a possible burst.

There are oil and water storage tanks equipped with valves at the outlet of each tank to control the flow rates. After the storage tanks, progressive cavity pumps are located to maintain the liquid flow rates. After the progressive cavity pumps, there are manual bypass valves to obtain low flow rates, and pressure relief valves for excessive pressure control. Following the valves, there are 2 copper-tube type heat exchangers 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 oil and water flow through the mixing tee to form the oil-water two-phase flow. The current test section is composed of two 21.1-m (69.3-ft) long straight transparent pipes, connected by a 1.2-m (4.0-ft) long PVC bend to reduce the disturbance to the flow pattern due to a sharp turn. The pipeline has a 0.0508-m (2.0-in.) internal diameter. The upward branch of the test section consists of: a 13.8-m (45.3-ft) long flow developing section (L/D = 272.0), two short pressure drop sections 5.2-m (17.0-ft) and 3.3-m (11.0-ft) long, one long pressure drop section combining the two short sections, one 5.5-m (18.1-ft) long fluid trapping section (L/D = 108), and a 1.8-m (6.0-ft) long measurement section. The downward branch of the test section is designed and built similar to the upward branch. The transparent pipes are instrumented to permit continuous monitoring of temperature, pressure, differential pressure, holdup and inclination.

All the modifications related with the three phase gas-oil-water facility for this study can be found in April 2007 Advisory Board meeting report.

Test Fluids

The fluids that are used in the experiments consist of refined mineral oil (Tulco Tech 80) and tap water. The same oil used by Keskin and Vielma is used in this study for maintaining the same fluid properties. All the oil has been replaced with the same fresh oil for this study. The physical properties of the oil are given below:

- 32.2 °API gravity.
- Density: 858.75 Kg/m3 @ 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 characterization measurements of Tulco Tech 80 mineral oil have been performed in ChevronTexaco labs. The changes in density and viscosity with temperature at three different flow rates are given in Figs. 2 and 3, respectively.

Testing Range

In this study, a large number of data points are collected at various conditions in terms of both fluid velocities and inclination angles. Superficial oil and water velocities range from 0.025 to 1.75 m/sec. These oil and water flow rates were determined in order to obtain the flow pattern boundaries clearly. Moreover, the limits of the facility were taken into consideration. Pipe inclination angles of 0^0, $\pm 1^0$, $\pm 2^0$ and -5^0 were covered in this study.

Droplet Size Data

Droplet size and its distribution is one of the main interests for this study. Image analysis technique by using high speed camera was used to determine the droplet size and its distribution as used in Vielma. This technique was chosen because of its non-intrusive nature which does not disturb the droplets during the flow.

One of the ways to compare drop size distributions is to use a characteristic mean diameter called Sauter Mean Diameter (D_{32} or SMD). SMD can be described as the diameter of a drop having the same volume to surface area ratio as the whole population. The SMD can be thought of as the ratio of the particle volume to surface area in a distribution.

$$SMD = \left(\sum_{i=1}^{N} N_i \delta_i^3 \right) \Big/ \left(\sum_{i=1}^{N} N_i \delta_i^2 \right). \qquad (1)$$

Where Ni is defined as the number of droplets in a bin i and δi s the middle droplet diameter of its size range.

In this study, three probabilistic distributions, which are normal, lognormal and Rosin Rammler, were used to characterize the experimental droplet size data. Detailed descriptions for the used probabilistic distribution are given as follows;

Normal Distribution

The Normal distribution (sometimes referred as the Gaussian distribution) is a continuous, symmetric distribution with various uses in all aspects of statistics. It is completely specified by two parameters: the mean (μ) and the variance σ^2. The mean of a Normal distribution is located at the center of the density and can be any real number. The variance of a Normal distribution measures the variability of the density distribution and can be any positive real number. The standard deviation σ is the square root of the variance and is used more often for its interpretability.

For a Normal random variable, the probability density function (PDF) is

$$f(d) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2} \left(\frac{d-\mu}{\sigma} \right)^2 \right]. \qquad (2)$$

The cumulative distribution function (CDF) of a Normal random variable is

$$F(d) = \Phi([d-\mu]/\sigma). \qquad (3)$$

Where, Φ is the Laplace integral.

$$\Phi(d) = \frac{1}{\sqrt{2\pi}} \int_0^d e^{-t^2/2} dt. \quad (4)$$

Log-normal Distribution
The Log-normal distribution is frequently used to represent the size of solid particles. The Log-normal distribution derives from the Normal or Gaussian distribution by replacing the independent variable with the logarithm of the particle diameter.

For a Log-normal random variable the probability density function (PDF) is

$$f(d) = \frac{\exp\left(-\frac{1}{2}\left(\frac{\ln d - \mu}{\sigma}\right)^2\right)}{d\sigma 2\pi}. \quad (5)$$

The cumulative distribution function (CDF) of a Log-normal random variable is

$$F(d) = \Phi([\ln d - \mu]/\sigma). \quad (6)$$

Rosin-Rammler Distribution
The Rosin-Rammler distribution is described by the following relation (Mugele and Evans, 1951)

$$F(d) = 1 - \exp\left(-(d/\alpha)^\delta\right). \quad (7)$$

Where, $F(d)$ is the cumulative volume fraction of the drops that have diameters less than d and α, δ are the parameters of the distribution; α is the size corresponding to (1-F(d)) =0.3679 and δ is the slope of the line. Therefore, this distribution can be described only by the two parameters α and δ. Its simple form makes it appealing for engineering calculations (Angeli and Hewitt).

In order to determine which probability distribution represents the droplet size data best, goodness of fit (GOF) test was performed. To determine the best distribution type for the droplet sizes a software EasyFit 3.0 was used. In this software there are three types of GOF tests which are; Chi-Squared, Kolmogorov-Smirnov and the Anderson-Darling Tests. Chi-Squared GOF was selected as a first test to determine the distribution type.

Uncertainty Analysis

There is an inherent associated error in every measurement. The definition of error is the difference between the true value of a parameter and the measurement obtained. Since the true value or the error is unknown in any experimental study, uncertainties and uncertainty analysis should be used to determine the limits of errors, and show the reliability of experimental data. In this study, an uncertainty analysis was performed for pressure gradients, temperature values, holdup, flow measurement, droplet size measurement and phase velocities.

Errors can be divided into two parts, random and systematic errors. Random errors affect the test data randomly. On the other hand, systematic errors stay the same during the test. Random uncertainty estimates the limits of random errors and systematic uncertainty estimates the limits of systematic errors. The following is the detailed explanation for random, systematic and combination of both random and systematic errors.

Random Uncertainty
Experimental data can be used to obtain the random uncertainty. Assuming a Gaussian distribution for N number of data points of a parameter, the standard deviation is,

$$S_X = \left[\sum (X_i - \bar{X})^2 / (N-1)\right]^{1/2}. \quad (8)$$

The standard deviation of the average can be obtained using,

$$S_{\bar{X}} = S_X / \sqrt{N}. \quad (9)$$

Systematic Uncertainty
Systematic errors affect every measurement of a parameter in same manner. Therefore, experimental data can not be used to estimate the systematic uncertainty. There can be several sources for the systematic uncertainty during experiments. In this study, the main error source for the systematic error is the calibration of the instruments.

The systematic uncertainty was calculated from the calibration errors for pressure, differential pressure, and temperature measurements. For liquid holdup measurement the systematic uncertainty was estimated based on the experience.

Combination of Random and Systematic Uncertainties
Random and systematic uncertainties should be combined to evaluate their combined effect to the experimental data. The total random uncertainty can be calculated as follows:

$$S_{\bar{X},R} = \left[\sum (S_{\bar{X},i})^2\right]^{1/2}. \quad (10)$$

The total systematic uncertainty can be defined as follows, where b_i is the systematic error for each source of systematic uncertainty.

$$B = \left[\sum (b_i)^2\right]^{1/2} . \qquad (11)$$

Therefore, the combined uncertainty is,

$$U_{95} = \pm t_{95,v}\left[(B/2)^2 + \left(S_{\bar{X},R}\right)^2\right]^{1/2} . \qquad (12)$$

Where; $t_{95,v}$ is the student's t distribution with a 95% confidence interval. The test data can be expressed as $\bar{X} - U_{95} \le X \le \bar{X} + U_{95}$. Then, the X value will be between $\left(\bar{X} - U_{95}\right)$ and $\left(\bar{X} + U_{95}\right)$ 95% of the time.

Uncertainty Propagation
For any experimental study, it is essential to combine the effect of different parameters in order to calculate propagation of the desired parameter. There are three commonly used methods for the uncertainty propagation: Taylor's Series uncertainty propagation, Dithering, and Monte Carlo simulation. For this study, Taylor's Series method was used to calculate the uncertainty propagation for the pressure drop, superficial velocities, mixture velocity, holdup, holdup ratio, and actual oil and water velocities.

If y is a function of independent variables a, b, c...., the uncertainty of y will be described as a function of independent uncertainties of a, b, c...., and are expressed as follows:

$$U_y = \sqrt{\left[\left(\frac{\partial y}{\partial a}\right)^2 (U_a)^2 + \left(\frac{\partial y}{\partial b}\right)^2 (U_b)^2 + \left(\frac{\partial y}{\partial c}\right)^2 (U_c)^2 + ...\right]} \quad (13)$$

Table 1 shows all the uncertainty analysis results for the measurement in this experimental study. All the uncertainty propagation is shown in Table 2.

Error Analysis

For each model in droplet size comparison, an error estimate was performed by using six parameters; these parameters are presented in Table 3.

Experimental Results

The experimental data of flow pattern, pressure drop, holdup, phase distribution, drop size and distribution, actual velocities and droplet size comparison against existing models are discussed for different inclination angles (0°, ±1°, ±2° and -5°) in this section. Trallero and Zhang et al. (2003) flow pattern prediction models were compared against the experimental data obtained in this study. Zhang et al. model was also used for pressure gradient and holdup comparison. Hinze (1955), Kubie and Gardner (1977), Angeli and Hewitt (2000), Brauner (2001) and Kouba (2003) models were used for d_{max}, d_{min} and SMD comparisons.

For the experimental results section, only representative inclination angles will be discussed for upward and downward flow. A complete set of the data and graphs can be found in Atmaca (2007).

Flow Pattern

Experimental flow pattern maps were generated by examining the images and videos obtained from high speed camera. The superficial velocities for each phase vary between 0.025-1.75 m/s. Figure 4 shows the experimental flow patterns for -1° of inclination angles respectively. By changing superficial velocities of each phase following flow patterns were observed:

- Stratified Flow (ST) (Fig. 5)
- Stratified with Mixing Interface (ST&MI) (Fig. 6)
- Dispersion of Oil in Water over Water Layer (DO/W&W) (Fig. 7)
- Dual Dispersion (Dispersion of oil in water and Dispersion of water in oil) (DO/W &DW/O) (Fig. 8)
- Dispersion of oil in water (DO/W) (Fig. 9)
- Dispersion of water in oil (DW/O) (Fig. 10)
- Transition stratified to stratified mixing interface (TRNS ST to ST&MI) (Fig. 11)
- Dispersion of water in oil under oil layer (DWO&O) (Fig. 12)

Experimental flow pattern maps were compared against Trallero's model and Zhang et al. unified model. Trallero's model predicted the most of the flow pattern boundaries well except stratified flow pattern (ST) (Fig. 13).

Although Zhang et al. model was developed for three phase gas-oil-water, for this study, only oil-water part is used. In oil-water unified model, there are only two boundaries which stand for the boundaries of oil in water (O/W) and water in oil (W/O). Zhang et al. model predicted the water in oil (W/O) boundary well in all inclination angles, while oil in water (O/W) flow pattern boundary was under-predicted. Figures 14 and 15 show the comparison of experimental flow pattern against Zhang et al. unified model prediction for -2° and +2° inclination angles, respectively.

Pressure Gradients

Figure 16 shows the pressure gradient data for v_{so}=0.025 m/s and its comparison between Trallero, Alkaya and Vielma data for the similar conditions. As expected, the pressure gradient increases with increasing superficial water velocity. The differences are mainly due to the different oil viscosities. The best match was observed with Vielma since the same oil is used in this study.

Total pressure gradient for two-phase flow has three components; frictional, acceleration and gravitational pressure gradients. For horizontal oil-water flow, acceleration and gravitational components can be neglected. For inclined flows, while the acceleration component can still be neglected, the gravitational component becomes very significant. For inclined flow, the measured pressure drop was corrected for the liquid in the pipe. Since the pipe is filled with oil-water mixture, the total pressure gradient can be obtained from the measured pressure drop using;

$$\frac{\Delta p_t}{\Delta L} = \frac{\Delta p_m}{\Delta L} + \rho_m g \sin\beta . \qquad (14)$$

Figure 17 shows the pressure drop for different superficial oil velocities as a function of superficial water velocities for +2° (upward flow). The general behavior, which is the increase in total pressure gradient with increasing superficial water velocity, is similar to that of horizontal configuration. For low superficial water and oil velocities, the dominant pressure gradient component is the gravitational component. As the velocity of each phases increase, the frictional component starts becoming dominant

Figure 18 is the pressure gradient graph for the -2° downward flow. Since negative pressure gradient values can exist, pressure drops were plotted in Cartesian scale. In downward flow, the existence of a minimum pressure gradient for a certain superficial water and oil velocities was observed.

The experimental pressure gradient data obtained in this study for different inclination angles were compared against the Zhang et al. model. Figure 19 shows the pressure gradient comparison against Zhang et al. model for horizontal case. The model predicts the pressure gradient within ±20 % error band. Figure 20 is the comparison of pressure gradient obtained for +1° of inclination angle with Zhang et al. model. The model predicts the pressure gradient within ±15 % error band. For most of the cases the pressure gradients were over predicted by the model. The model predictions were observed to be reasonably well for low superficial velocities while they were worsened as the superficial velocities increased. Table 4 shows the error analysis of the Zhang et al. model against experimental data.

Figure 21 is the comparison of Zhang et al. model against experimental data for minimum pressure gradient behavior. The model shows minimum pressure gradient behavior but not as pronounced as the experimental data. Figure 22 shows only the minimum pressure gradient area for v_{so}=0.025 m/s and v_{so}=0.100 m/s.

Water Holdup

Quick closing valves are used for holdup measurements with raising the boom. A measured tape was attached parallel to the boom to measure the oil and water level in trapping section.

Figures 23-24 and Figs. 25-26 show the water holdup and water holdup ratio, which is the ratio of no-slip holdup to experimental holdup, for -2° and +2° of inclination angles, respectively. Due to separation problems, holdup data was not collected for v_{so}=1.750 m/s and v_{sw}=1.750 m/s for ±2° inclination angles. In C_w/H_w graph, for +2° inclination angle, all the values start from less than one which means oil flows faster than water. Moreover, the other values are very close to one which means there is no or negligible slippage. Water mostly flows slower than oil for +2° inclination angle. For -2° inclination angle this ratio starts more than one which means water flows faster.

For the better understanding of slippage of the phases in different operating conditions, the normalized drift velocity was plotted against the mixture velocity. The normalized drift velocity, v_N, and mixture velocity, v_m, are defined in Eqs. 15 and 16 respectively.

$$v_N = (v_w - v_o)/v_m . \qquad (15)$$

$$v_m = v_{sw} + v_{so} . \qquad (16)$$

Three different (low, medium and high) superficial oil velocities (v_{so}) were used in normalized drift velocity graphs. Figure 27 shows the normalized drift velocity -2° inclination angle. As expected, the largest v_N values can be seen for the lowest mixture velocity values for each individual superficial oil velocities. Generally, for each representative superficial oil flow rate, as the mixture velocity increases, normalized slip velocity approaches to zero which means there is no or negligible slippage between the phases. For v_{so}=0.050 m/s, the normalized slip velocity starts from high positive values, which means water flows much faster than oil. This is mainly due to the gravity effect.

Figure 28 is the normalized drift velocity graph with respect to mixture velocity for +2° inclination angle. As observed in -2° downward flow, the normalized drift velocity approaches zero with increasing mixture velocity. Normalized drift velocity for v_{so}= 0.050 m/s starts from large negative values, which means oil flows much faster than water. This difference between +2° and -2° inclination angle explains the physics of the flow. For upward flow (+2°), since the density of the water is greater than the density of oil, the gravitational force behaves like drag force for the water phase. The drag force slows the flow of the water with respect to the oil. The similar argument can be made for the downward flow (-2°).

The experimental water holdup for different inclination angles were compared against Zhang et al. model. Figures 29 and 30 show the comparisons for +1° and -1° inclination angles, respectively. Solid lines stand for the model predictions for the boundaries. The model predicts the holdups within ±15 % error band for both configurations. Table 5 shows the performance of the Zhang et al model against experimental data.

Phase Distribution

Conductivity probes were used to determine the phase distribution across the cross section of the pipe. Conductivity probes can determine the continuous phase in the pipe during different operating conditions. Same conductivity probe configuration was previously used in Vielma. For stratified (ST) and stratified with mixing interface (ST&MI) flow patterns, conductivity probes performed well. Due to the turbulence and the formation of drops, conductivity probes did not give reliable results for dispersion type flow patterns. The probes can not detect the small droplets.

Collecting conductivity probe data for each data point is a very slow process. Therefore, the phase distribution data were collected for three different oil/water ratios (v_{so}=0.050 m/s and v_{sw}=0.050 m/s, v_{so}=0.050 m/s and v_{sw}=0.100 m/s, v_{so}=0.100 m/s and v_{sw}=0.050 m/s) for each inclination angles using the new improved grid system (Fig. 31) with 120 data points in order to increase the accuracy of the data points.

Figure 32 shows the phase distribution of the phases for -2° inclination angle. The estimated layer was tried to be plotted with continuous line on each figure. In the middle of the figure, concave or convex structure was observed but this is because of the interpolation between the data points. Figure 33 shows the phase distribution of each phases for +2° inclination angle for upward flow.

Hot Film Anemometer

An attempt was made to measure in-situ velocities of the phase by using hot film anemometer. This technique was abandoned due to several disadvantages of this technique for oil-water flow such as; fragile nature of probe, inconsistent calibration curves, contamination of the probe which results change in its resistance.

Droplet Size Distribution

Droplet size and its distribution is one of the main interests for this study. Image analysis technique by using high speed camera was used to determine the droplet size and its distribution as used in Vielma. This technique was chosen because of its non-intrusive nature which does not disturb the droplets during the flow. It is not applicable to all combination of flow rates (especially high flow rates with low water cut). Location of the high speed camera was dependent on flow pattern. For stratified (ST), stratified mixing (ST&MI) and dispersion of oil in water over water layer (DO/W&W) flow patterns, entire pipe was shot in different shutter speed. For dispersion of oil in water (O/W) and water in oil (W/O), the camera was located close to the pipe and only small section of the pipe was shot. In oil in water (O/W) and water in oil (W/O) type of flow pattern, it was assumed that the distributions of the droplets are homogenous all around the pipe. In dual continuous (O/W&W/O) flow pattern, the pictures were taken from the bottom and the top of the pipe. The number of the droplets obtained from the pictures is flow pattern dependent but in all cases minimum 400 droplets were tried to be counted.

Droplets were counted by using Image ProPlus 5.1 software. In each picture every droplet was counted one by one. Since droplets are not counted automatically, the repeatability of the counting droplets should be checked. Figure 34 shows the repeatability of this technique. Droplets were counted from the same picture by two different people. Dispersion of oil in water over water layer (DO/W&W) flow pattern was selected as a sample because it was divided into ten sections which make it more sensitive. The top section refers to the top of the pipe and the bottom section refers to the bottom of the pipe. The agreement between two counts was good.

Figures 35 and 37 show the droplet size distribution and probability distributions for oil in water flow (O/W) and water in oil (W/O) patterns, for +2°

inclination angle, respectively. The figures show all the probability distributions tested to represent droplet size data. In both cases log-normal is the best probability distribution to represent the droplets size data. Rosin Rammler distribution type failed to represent any of the cases for water droplets.

Figure 39 shows the droplet size data and the three different probabilistic distributions for stratified with mixing interface (ST&MI) flow pattern for $+2^{\circ}$ inclination angle. As stated in the previous flow patterns, log-normal represents the droplet size data best among the selected distribution types.

For dispersion of water in oil over water layer (DO/W&W) flow pattern, different procedure was applied since the droplet size distribution is not homogenous across the pipe cross section. Figure 41 shows the behavior of SMD as function of the height from bottom to top of the pipe for $+2^{\circ}$ inclination angle. The pipe was divided into 5 sections in each picture to see the SMD behavior clearly. The top and bottom of the y-axis in the graphs refer to the top and bottom of the cross section of the pipe, respectively.

Figures 42 and 43 show the droplet size distribution and probabilistic distributions for oil droplets and water droplets, respectively, for -1° inclination angle for dual continuous (O/W&W/O) flow pattern. The water droplets are in smaller size compared to oil droplets. For both of oil and water droplets, log-normal distribution worked well.

SMD was analyzed for each flow pattern. Increasing trend in SMD was observed with increasing dispersed phase superficial velocities for different inclination angles in oil in water (Fig. 36) and water in oil (Fig. 38). When the internal phase velocity increases, v_{so} and, v_{sw}, respectively, the SMD tends to increase for same continuous phase superficial velocity. As the percentage of internal phase increases, the droplets get closer, increasing the coalescence tendency, and resulting in larger droplets. No trend was observed for the effect of inclination angle. Figure 40 shows the SMD behavior with respect to v_{sw} for different inclination angles. Decreasing trend in SMD was observed with increasing superficial water velocities for different inclination angles. As the superficial water velocity increases, turbulence level increases and smaller oil droplets are formed. The size of SMD also depends on the oil layer thickness during the flow. No clear trend was observed for the effect of inclination angle. Figures 44 and 45 show the variation of SMD for oil and water droplets respectively for a constant superficial oil velocity (v_{so}=1.000 m/s) with changing superficial water velocity. Increasing trend in SMD was observed in water droplets with increasing superficial water velocities for different inclination angles. For water droplets, this can be explained by coalescence tendency as discussed in W/O type of flow pattern. Trend is not so clear for the oil droplets since there are only two data points in each inclination angles. No clear trend was observed with the change of inclination angle.

Droplet Size Comparison

The droplet size data were compared against the predictions by the existing models for d_{max}, d_{min} and SMD. In the literature, Hinze, Kubie and Garner, Angeli and Hewitt, Brauner and Kouba models exist to estimate the d_{max}. Kouba is the only model to predict the d_{min}. For SMD prediction, Angeli and Hewitt model, which is the only available model for SMD prediction, was used. The models work for fully dispersed cases. Therefore, comparisons are presented in following sections;

- Maximum diameter in O/W type dispersion
- Minimum diameter in O/W type dispersion
- SMD in O/W type dispersion
- Maximum diameter in W/O type dispersion
- Minimum diameter in W/O type dispersion
- SMD in W/O type dispersion

Maximum Diameter Comparisons-O/W

Figure 46 shows the comparison of experimental d_{max} with the model predictions for -1° of inclination angle, for different superficial oil velocities. Diamond points on the graph represent the experimental data points. Angeli and Hewitt, Kubie and Gardner models over-predicted the experimental d_{max}. On the other hand, Kouba under-predicted the experimental data. Hinze and Brauner showed the best performance. Hinze predicted d_{max} the best among all models. Table 6 shows the error analysis for each model.

Minimum Diameter Comparisons-O/W

Figure 47 shows the comparison of d_{min} data against Kouba model for -1° of inclination angle, for different oil superficial velocities. The model under-predicted for most of the cases. Table 7 shows the statistical parameters for Kouba model.

SMD Comparisons-O/W

Figure 48 shows the comparison of experimental SMD against Angeli and Hewitt model for -1° of inclination angle. Angeli and Hewitt model over-predicted the experimental SMD data for all cases. Table 8 shows the error analysis for the comparison.

Maximum Diameter Comparisons-W/O

Figure 49 shows the comparison of d_{max} against existing models for different superficial water velocities for -1°. Kubie and Gardner model over predicted the experimental d_{max} for all inclination angles, where all the other models under predicted experimental d_{max} data. Brauner model predicted the d_{max} the best among all models. An error analysis can be found in Table 9.

Minimum Diameter Comparisons-W/O

Figure 50 shows the comparison of d_{min} against Kouba model for varying superficial water velocities for -1°. The model under-predicted d_{min}. Table 10 shows the error analysis for Kouba model.

SMD Comparisons-W/O

Figure 51 shows the performance of Angeli and Hewitt model against experimental SMD obtained in this study for -1°. Angeli and Hewitt model under-predicted experimental SMD data that obtained in this study. Error analysis can be found in Table 11.

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Table 1: Uncertainty Analysis Results for Oil-Water Facility

Instrument	Random Uncertainty	Systematic Uncertainty	Degrees of Freedom	Overall Uncertainty (U_{95})
PT1 (psi)	0.70%	5.26%	Infinity	5.44%
PT1_1 (psi)	0.57%	9.80%	Infinity	9.87%
PT2 (psi)	1.95%	10.34%	Infinity	11.05%
PT3 (psi)	2.57%	4.22%	Infinity	6.65%
PT4 (psi)	1.70%	2.86%	Infinity	4.44%
PT6 (psi)	2.56%	4.19%	Infinity	6.61%
PT7 (psi)	2.76%	3.74%	Infinity	6.66%
PT8 (psi)	0.00%	0.46%	Infinity	0.46%
DP1 (in H_2O)	0.08%	0.14%	Infinity	0.21%
DP2 (in H_2O)	0.03%	0.06%	Infinity	0.08%
DP3 (in H_2O)	0.03%	0.08%	Infinity	0.10%
DP4 (in H_2O)	0.02%	0.16%	Infinity	0.17%
DP5 (in H_2O)	0.03%	0.09%	Infinity	0.10%
DP6 (in H_2O)	0.02%	0.07%	Infinity	0.08%
TT1 (°F)	0.001	0.389	Infinity	0.39
TT2 (°F)	0.003	0.372	Infinity	0.37
TT3 (°F)	0.005	0.383	Infinity	0.38
TT4 (°F)	0.002	0.376	Infinity	0.38
TT5 (°F)	0.007	0.381	Infinity	0.38
TT7 (°F)	0.007	0.382	Infinity	0.38
TT8 (°F)	0.005	0.375	Infinity	0.38
WFM (gpm)	0.11%	0.16%	Infinity	0.27%
OFM (gpm)	0.11%	0.04%	Infinity	0.22%
WFM (gr/cm^3)	0.00%	0.05%	Infinity	0.05%
OFM (gr/cm^3)	0.00%	0.04%	Infinity	0.04%
Tape (inch)	1.00	0.10	Infinity	2.00
Droplet Size (mm)	0.012	0.010	Infinity	0.03

Table 2: Uncertainty Propagation Results

Measurement	Random Uncertainty	Systematic Uncertainty	Degrees of Freedom	Overall Uncertainty (U_{95})
Pressure Drop (Pa/m)	0.00503	0.04677	Infinity	0.04784
v_{sw} (m/s)	0.00003	0.00005	Infinity	0.00008
v_{so} (m/s)	0.00003	0.00001	Infinity	0.00007
v_M (m/s)	0.00005	0.00005	Infinity	0.00011
H_w	0.00459	0.02294	Infinity	0.02470
C_w/H_w	0.00644	0.02359	Infinity	0.02688

Table 3: Statistical Parameters

Definitions	Unit
$\varepsilon_1 = \left[\frac{1}{N}\sum_{i=1}^{N} e_{ri}\right]$	%
$\varepsilon_2 = \left[\frac{1}{N}\sum_{i=1}^{N} \lvert e_{ri}\rvert\right]$	%
$\varepsilon_3 = \sqrt{\frac{\sum_{i=1}^{N}(e_{ri}-\varepsilon_1)^2}{N-1}}$	%
$\varepsilon_4 = \frac{1}{N}\sum_{i=1}^{N} e_i$	mm/(Pa/m)
$\varepsilon_5 = \frac{1}{N}\sum_{i=1}^{N} \lvert e_i\rvert$	mm/(Pa/m)
$\varepsilon_6 = \sqrt{\frac{\sum_{i=1}^{N}(e_i-\varepsilon_4)^2}{N-1}}$	mm/(Pa/m)

Table 4: Pressure Gradient Evaluation against Zhang et al. Model

	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (Pa/m)	ε_5 (Pa/m)	ε_6 (Pa/m)
Pressure Gradient	73.93	125.76	863.08	155.26	194.91	319.84

Table 5: Water Holdup Evaluation against Zhang et al. Model

	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4	ε_5	ε_6
Water Holdup	1.43	9.65	27.23	0.01	0.04	0.04

Table 6: Maximum Diameter Model Evaluation for O/W Dispersions

Model	Flow Pattern	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (mm)	ε_5 (mm)	ε_6 (mm)
Hinze	O/W	-9.84	19.00	24.36	-0.22	0.28	0.40
Kubie & Gardner	O/W	449.36	449.36	153.14	5.14	5.14	0.76
Angeli & Hewitt	O/W	231.94	231.94	94.74	2.58	2.58	0.42
Kouba	O/W	-84.14	84.14	6.40	-1.07	1.07	0.43
Brauner	O/W	-16.26	22.13	23.93	-0.29	0.33	0.42

Table 7: Minimum Diameter Model Evaluation for O/W Dispersions

Model	Flow Pattern	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (mm)	ε_5 (mm)	ε_6 (mm)
Kouba	O/W	-38.75	43.49	29.67	-0.05	0.05	0.05

Table 8: SMD Model Evaluation for O/W Dispersions

Model	Flow Pattern	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (mm)	ε_5 (mm)	ε_6 (mm)
Angeli &Hewitt	O/W	199.32	199.32	65.83	1.17	1.17	0.16

Table 9: Maximum Diameter Model Evaluation for W/O Dispersions

Model	Flow Pattern	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (mm)	ε_5 (mm)	ε_6 (mm)
Hinze	W/O	-44.52	44.52	15.80	-0.82	0.82	0.68
Kubie & Gardner	W/O	205.04	205.04	84.70	3.31	3.31	1.84
Angeli & Hewitt	W/O	-57.88	57.88	13.04	-1.04	1.04	0.58
Kouba	W/O	-90.44	90.44	2.74	-1.54	1.54	0.65
Brauner	W/O	-40.60	41.46	17.86	-0.77	0.78	0.54

Table 10: Minimum Diameter Model Evaluation for W/O Dispersions

Model	Flow Pattern	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (mm)	ε_5 (mm)	ε_6 (mm)
Kouba	W/O	13.11	57.55	76.46	-0.01	0.03	0.04

Table 11: SMD Model Evaluation for W/O Dispersions

Model	Flow Pattern	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (mm)	ε_5 (mm)	ε_6 (mm)
Angeli &Hewitt	W/O	-61.74	61.74	11.72	-0.54	0.54	0.21

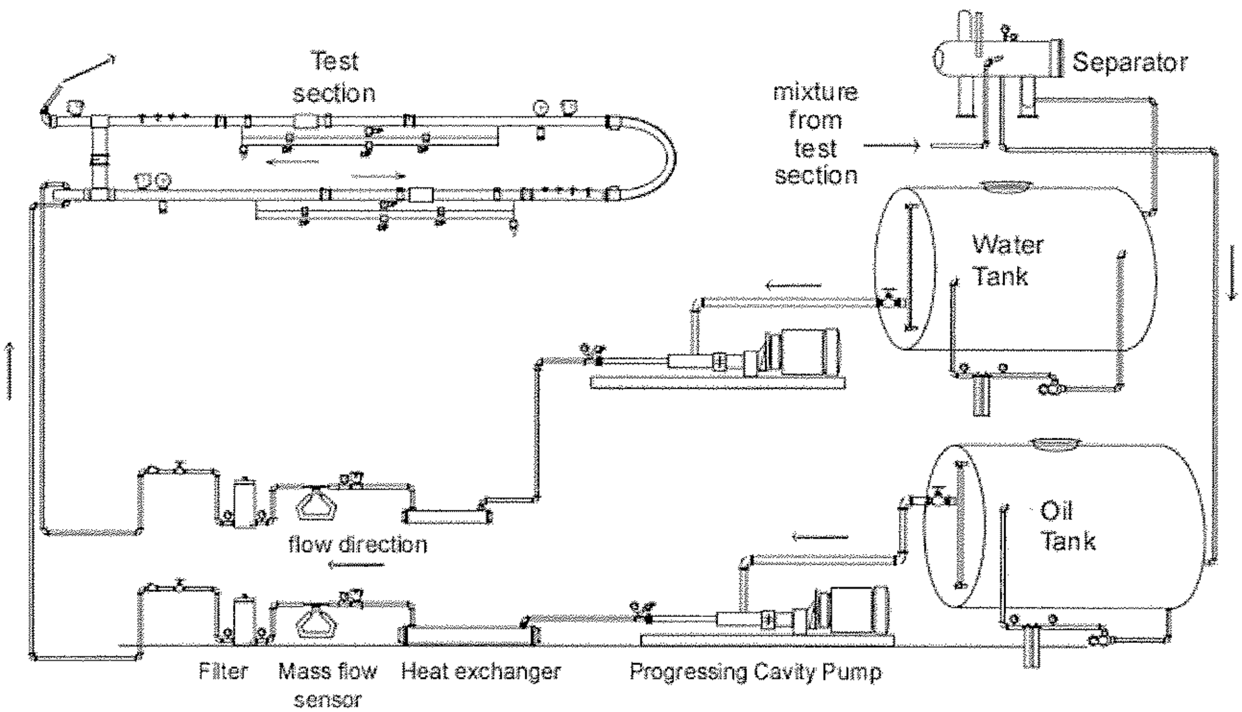

Figure 1: Schematic of the Facility

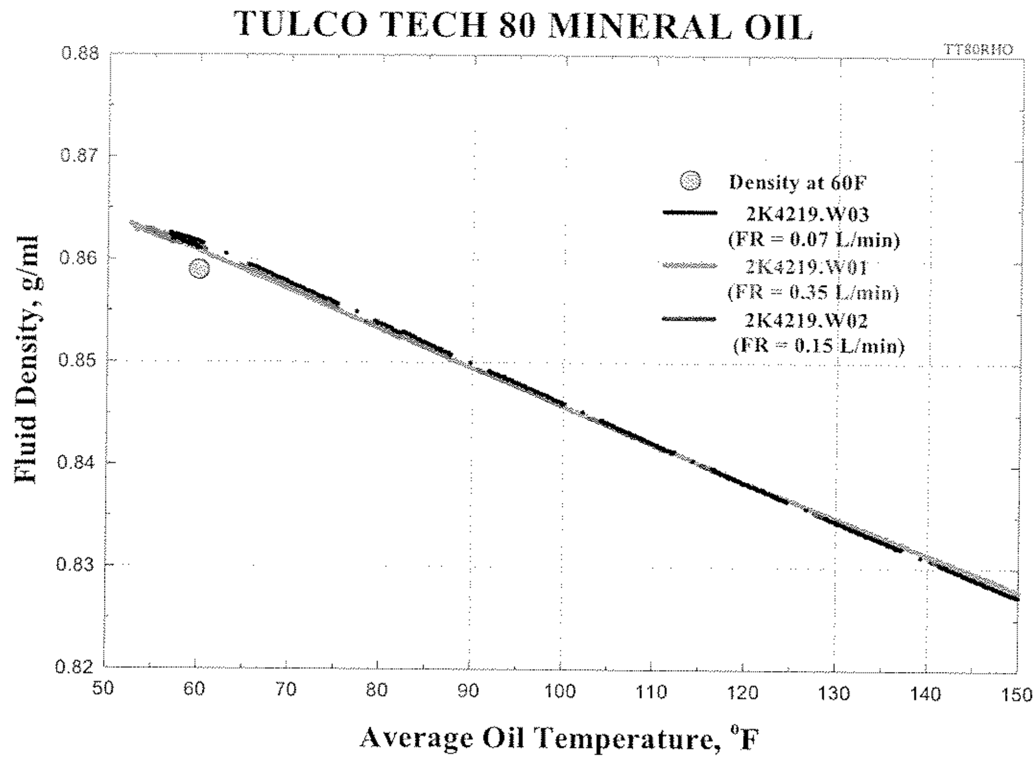

Figure 2: Change of Density with Temperature

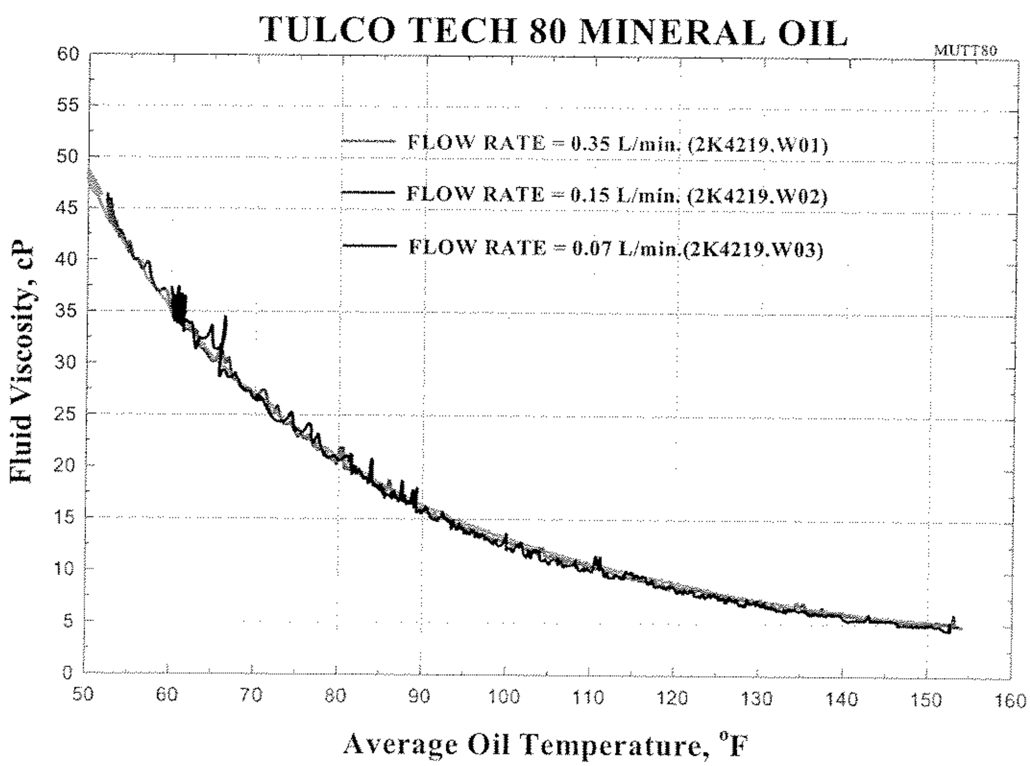

Figure 3: Change of Viscosity with Temperature

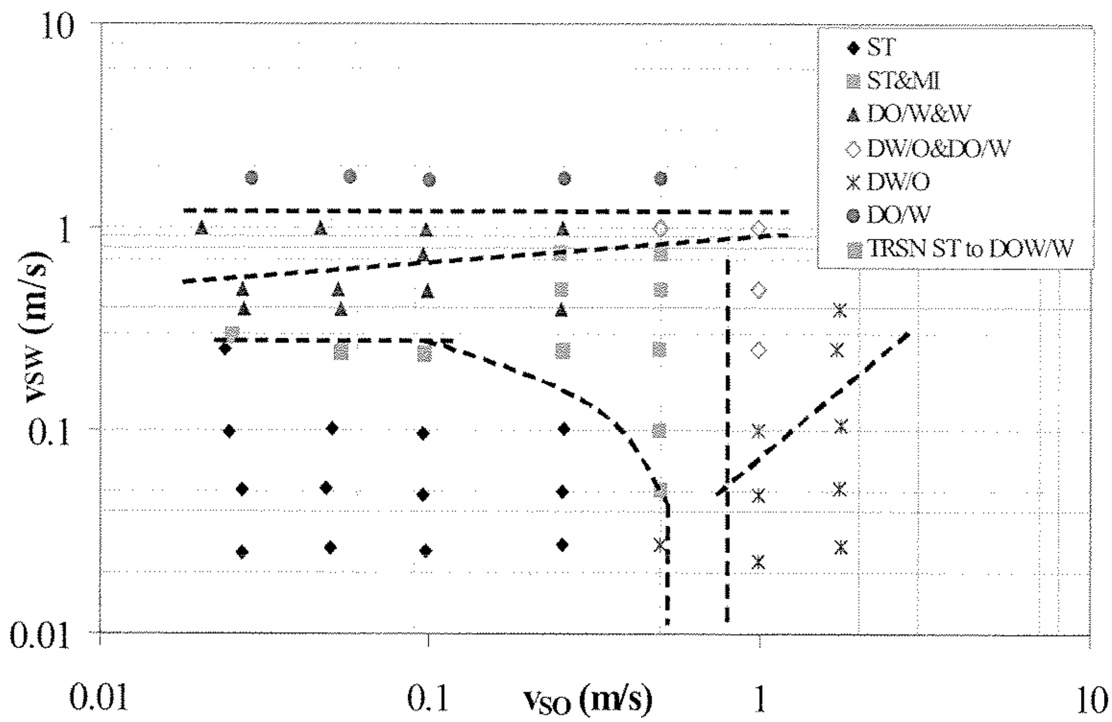

Figure 4: Experimental Flow Pattern Map (-1° Downward); Present Study

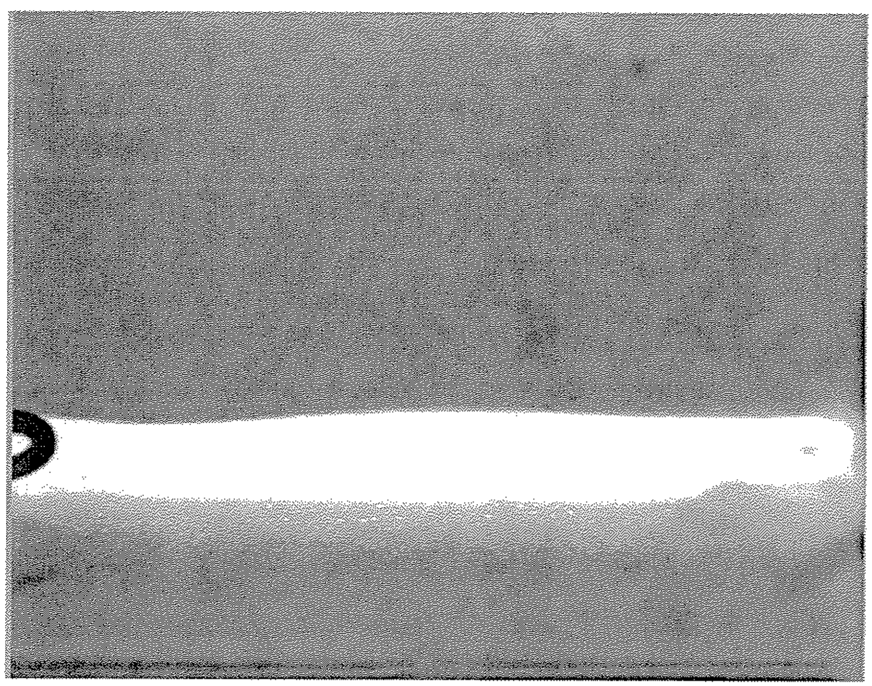

Figure 5: v_{so}=0.025 m/s_v_{sw}=0.025 m/s (ST)

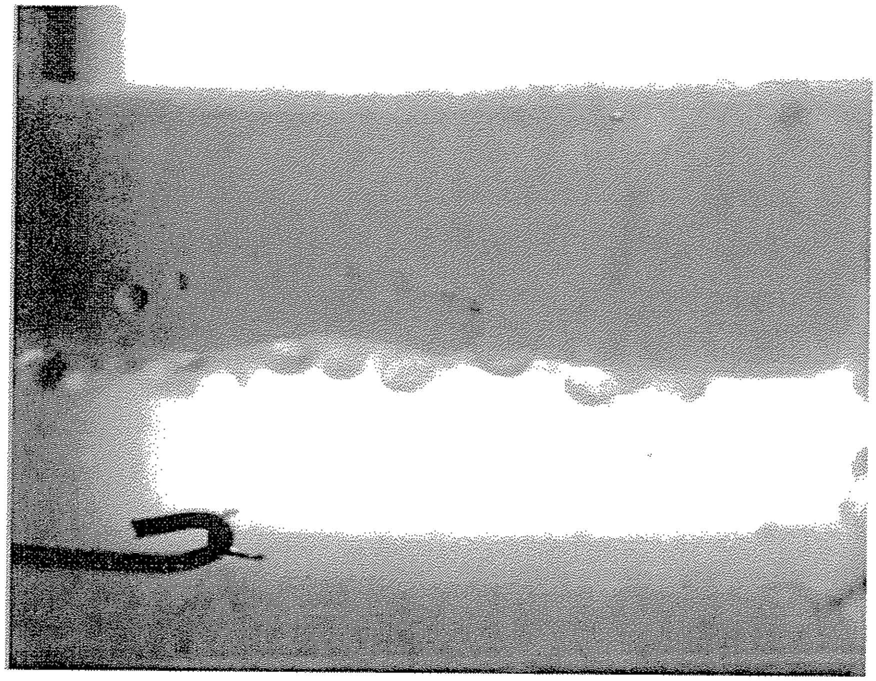

Figure 6: v_{so}**=0.250 m/s**_v_{sw}**=0.500 m/s (ST&MI)**

Figure 7: v_{so}**=0.050 m/s**_v_{sw}**=1.000 m/s (DO/W&W)**

Figure 8: v_{so}= 1.000 m/s_v_{sw}=0.400 m/s (DO/W &DW/O)

Figure 9: v_{so}= 0.050 m/s_v_{sw}=1.750 m/s (DO/W)

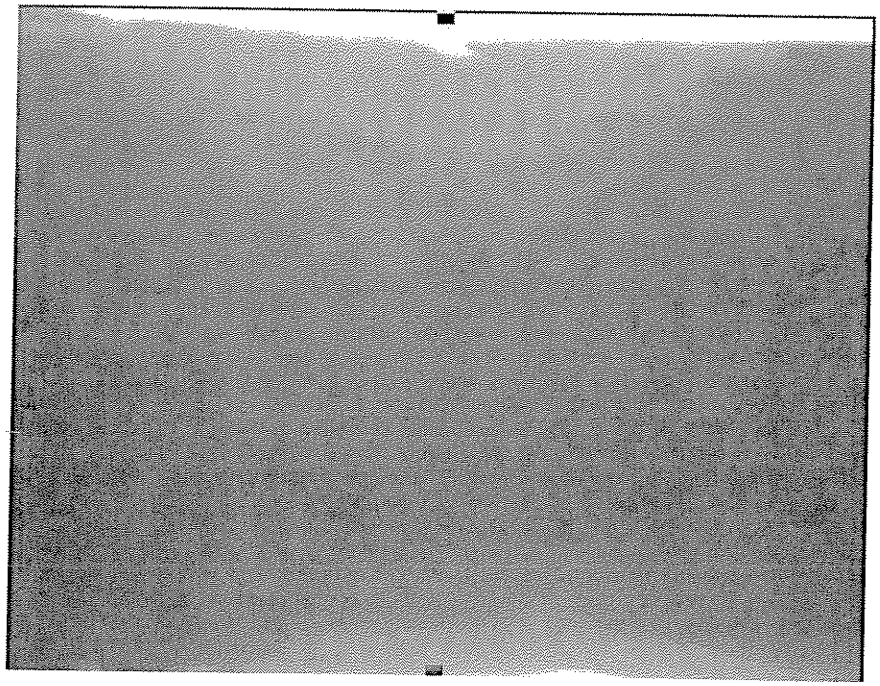

Figure 10: v_{so}= 1.750 m/s_v_{sw}=0.100 m/s (DW/O)

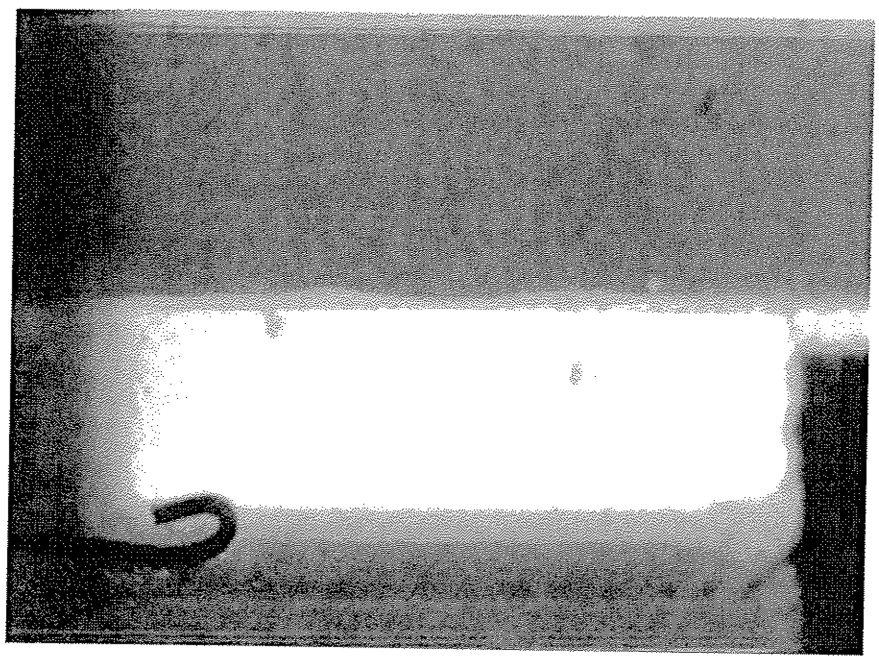

Figure 11: v_{so}=0.100 m/s_v_{sw}=0.250 m/s (TRNS ST to ST&MI)

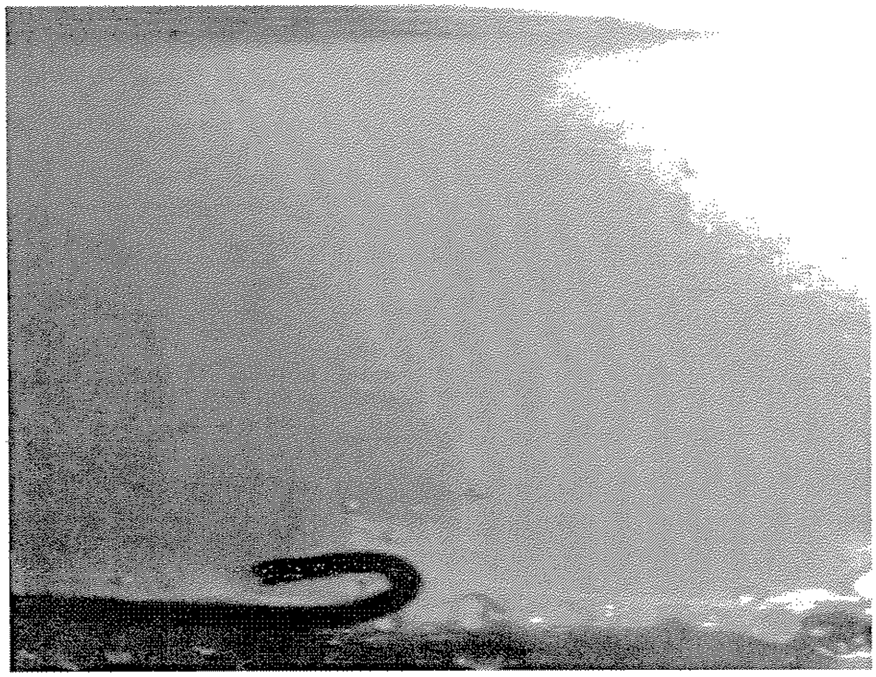

Figure 12: v_{so}=0.500 m/s_v_{sw}=0.025 m/s (DW/O&O)

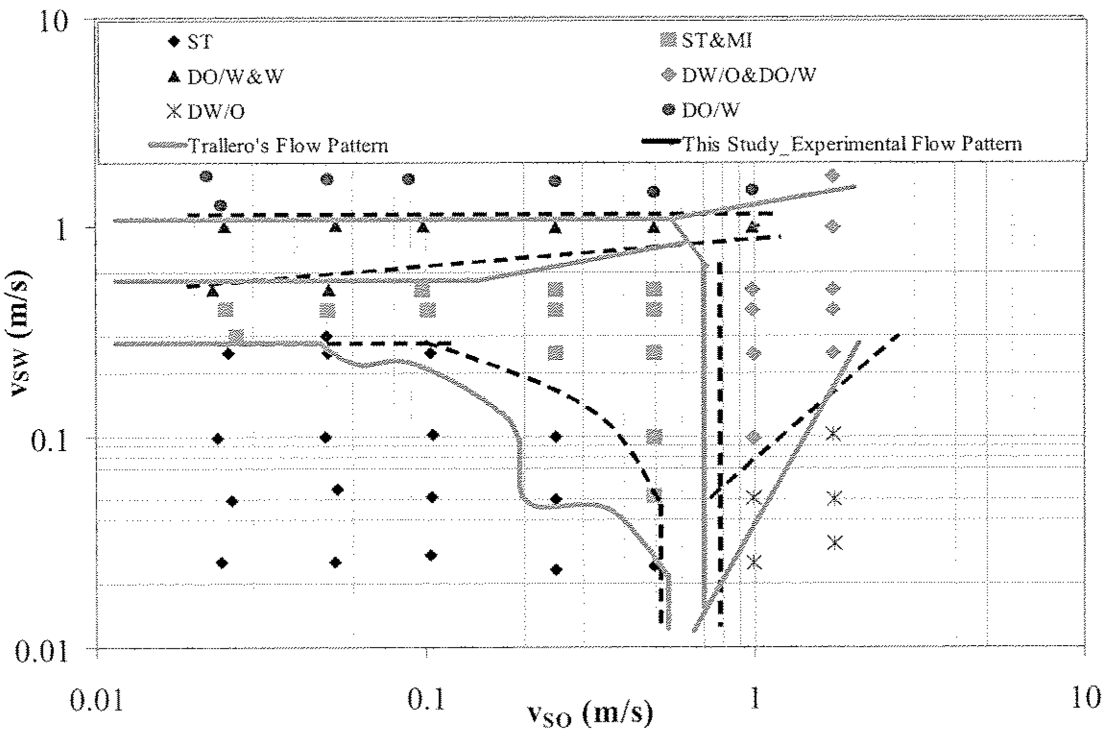

Figure 13: Comparison of Flow Pattern Boundaries (Model) Horizontal

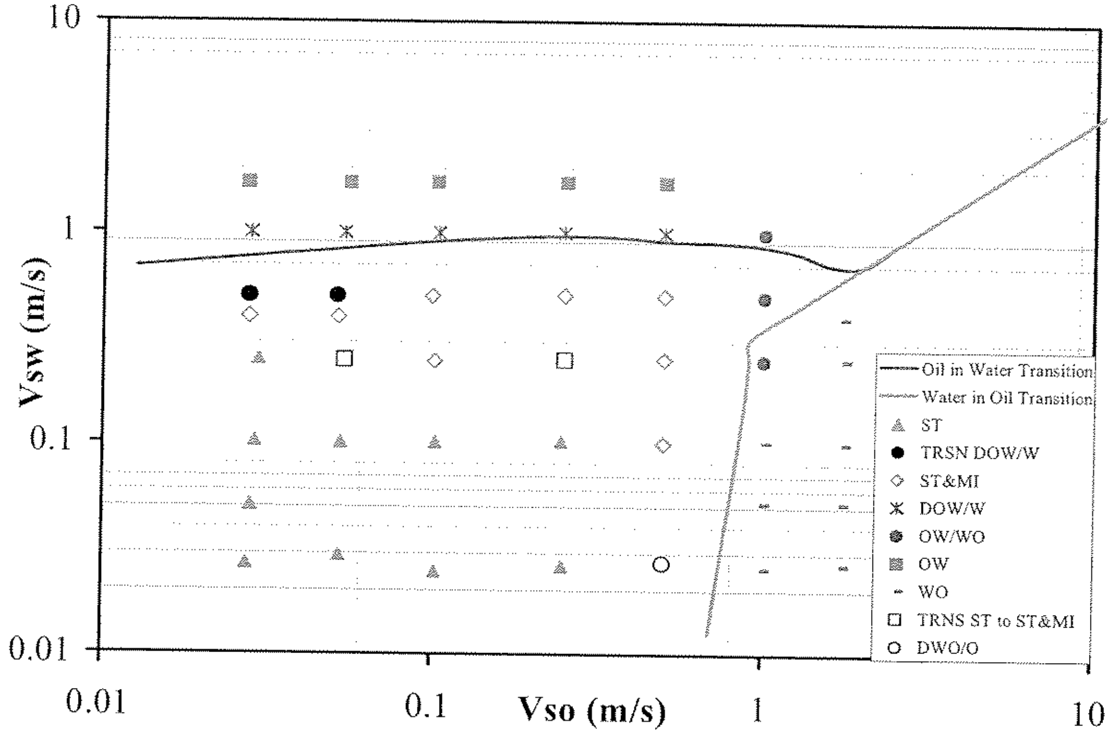

Figure 14: Comparison of Flow Pattern Boundaries (-2° Downward)

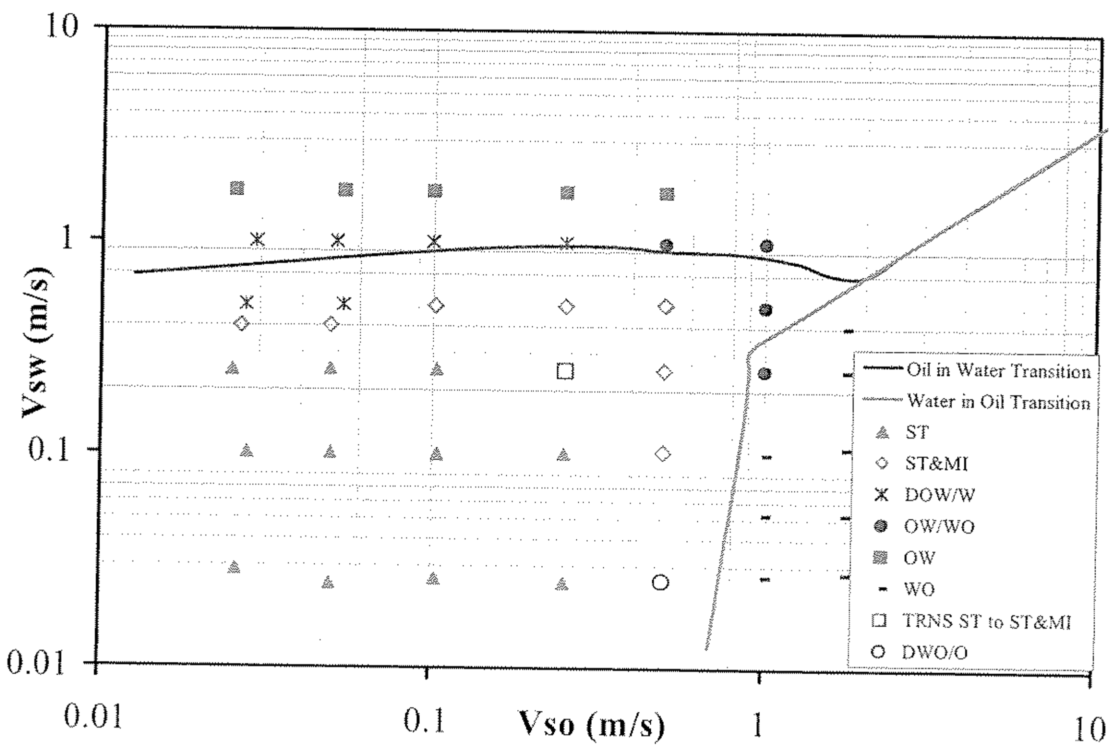

Figure 15: Comparison of Flow Pattern Boundaries (+2° Upward)

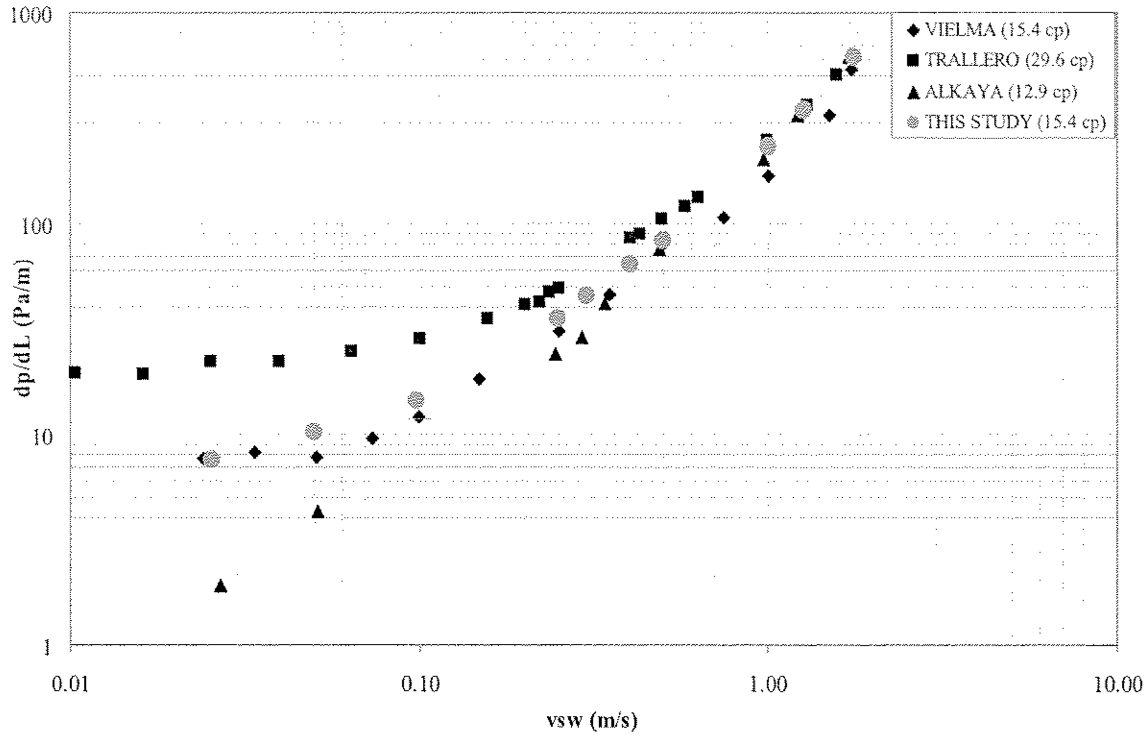

Figure 16: Pressure Drop Comparison (v_{so}=0.025 m/s)

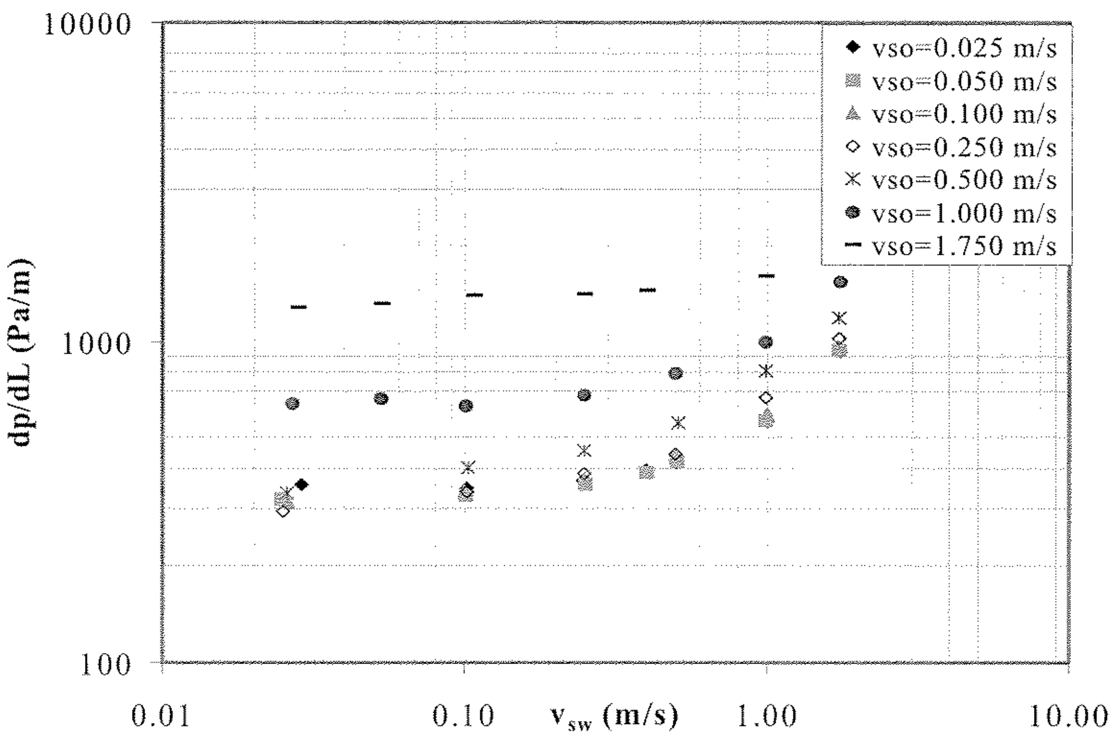

Figure 17: Experimental Pressure Gradients (+2° Upward)

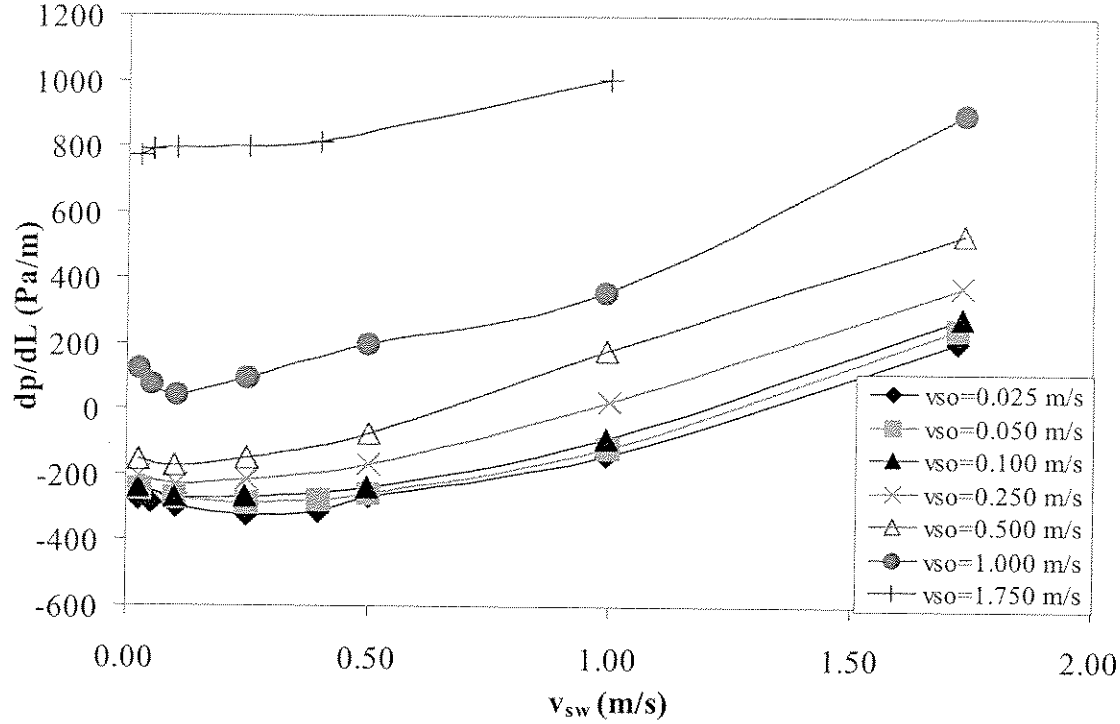

Figure 18: Experimental Pressure Gradients (-2° Downward)

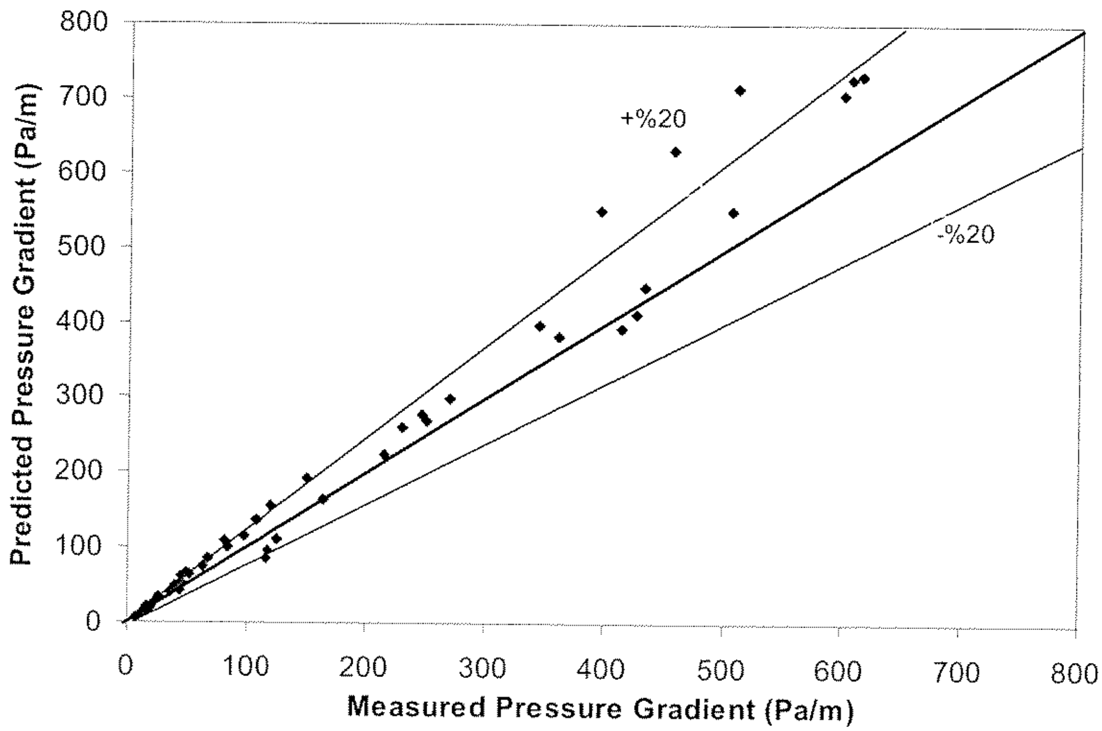

Figure 19: Unified Model Pressure Gradient Comparisons (Horizontal)

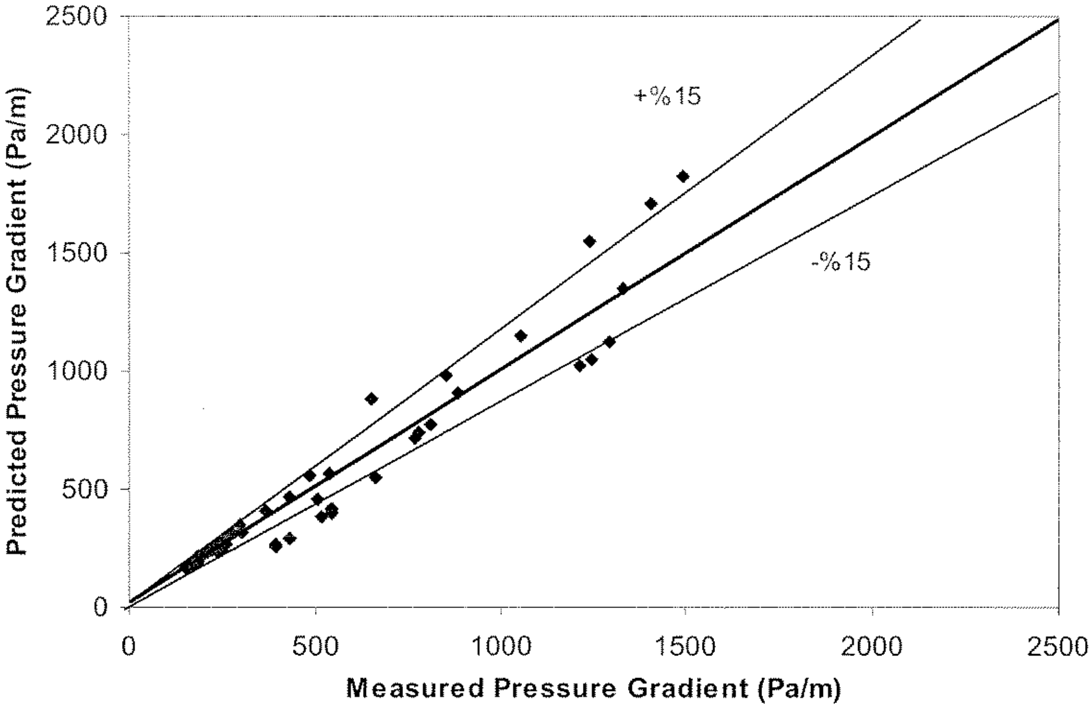

Figure 20: Unified Model Pressure Gradient Comparisons (+1° Upward)

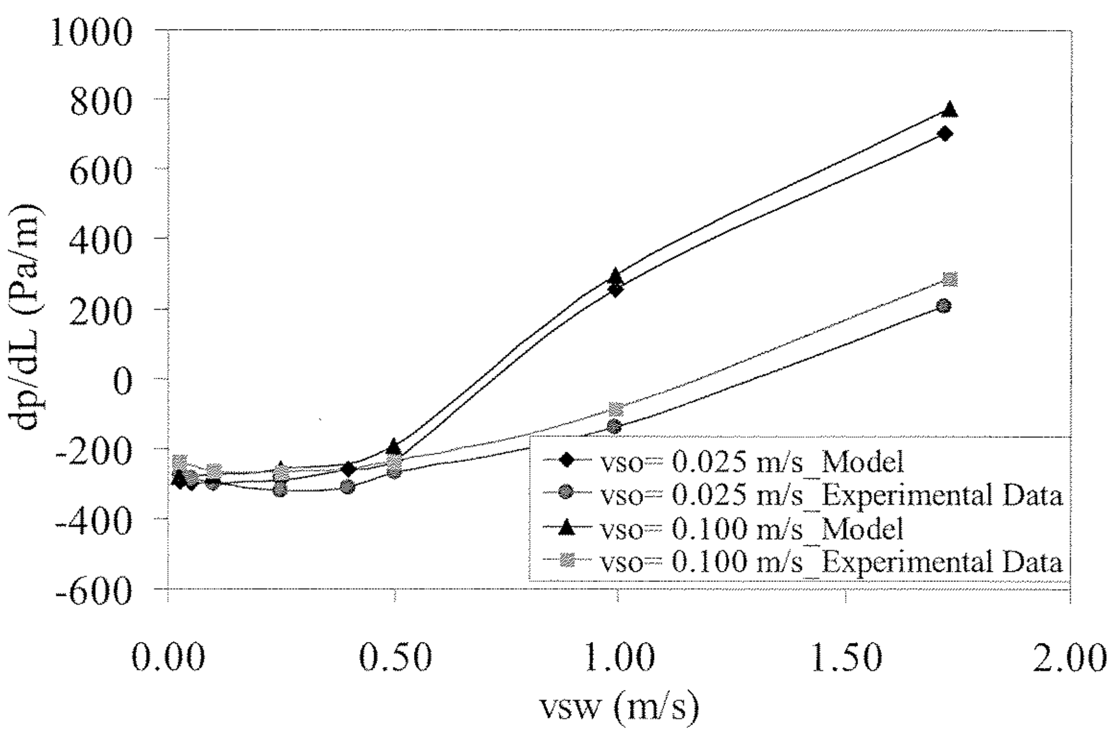

Figure 21: Minimum Pressure Gradient Comparison against Zhang et. al Unified Model (-2° Downward)

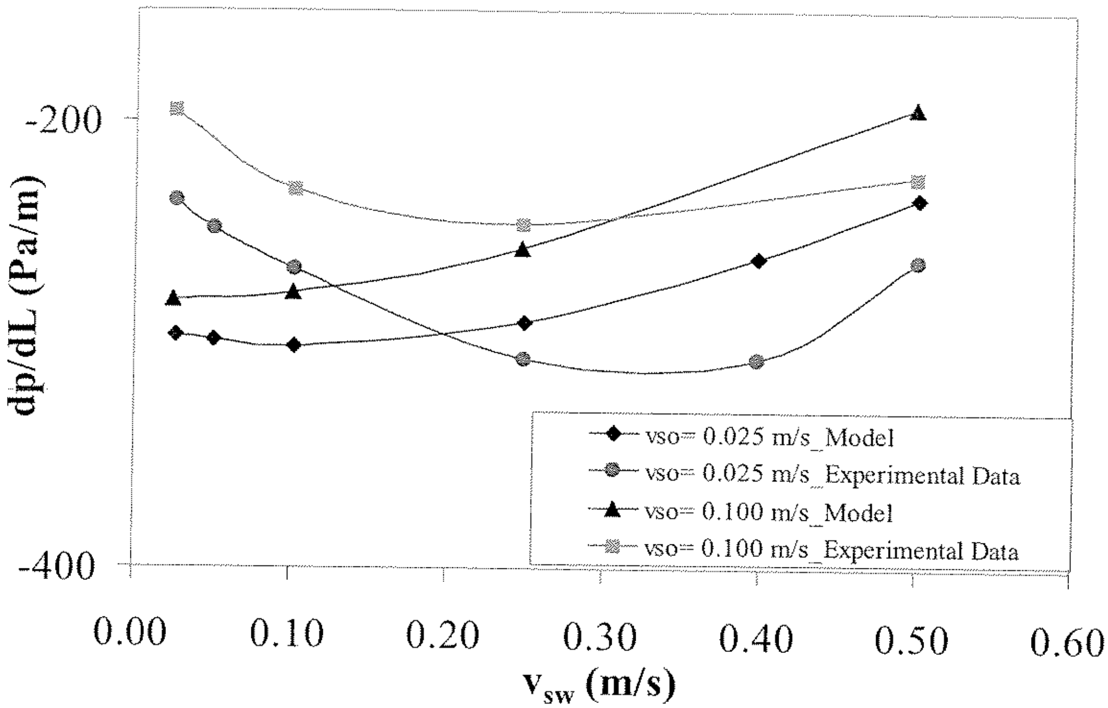

Figure 22: Minimum Pressure Gradient Comparison against Zhang et. al Unified Model (Small Area_-2° Downward)

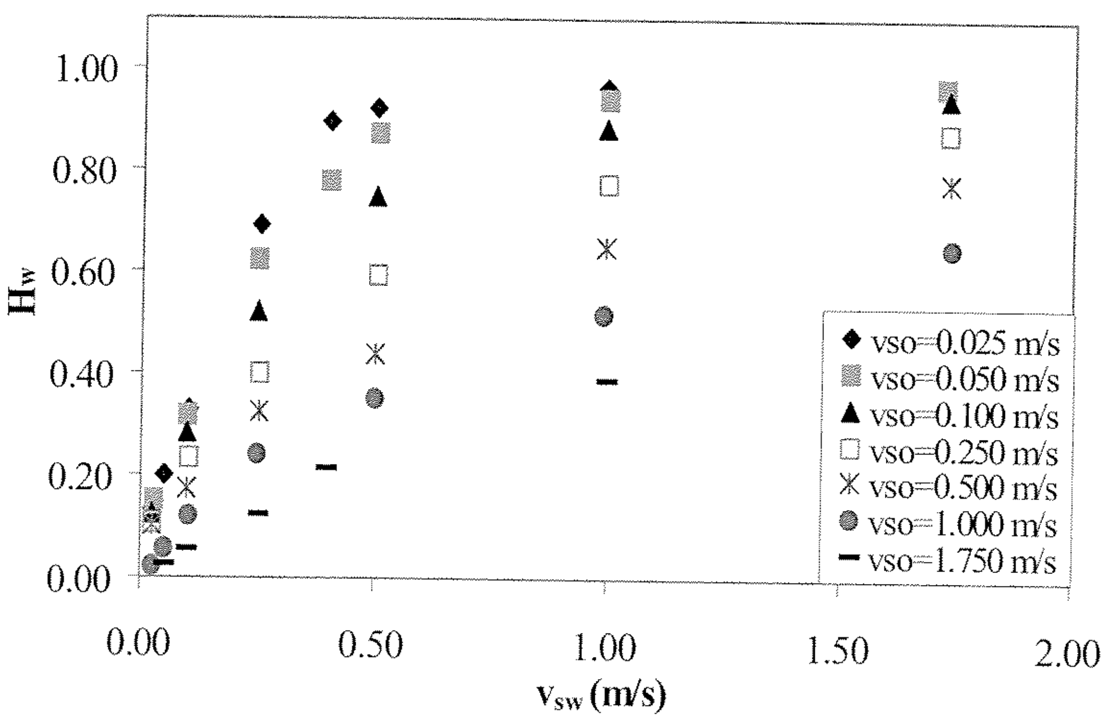

Figure 23: Experimental Water Holdup (-2° Downward)

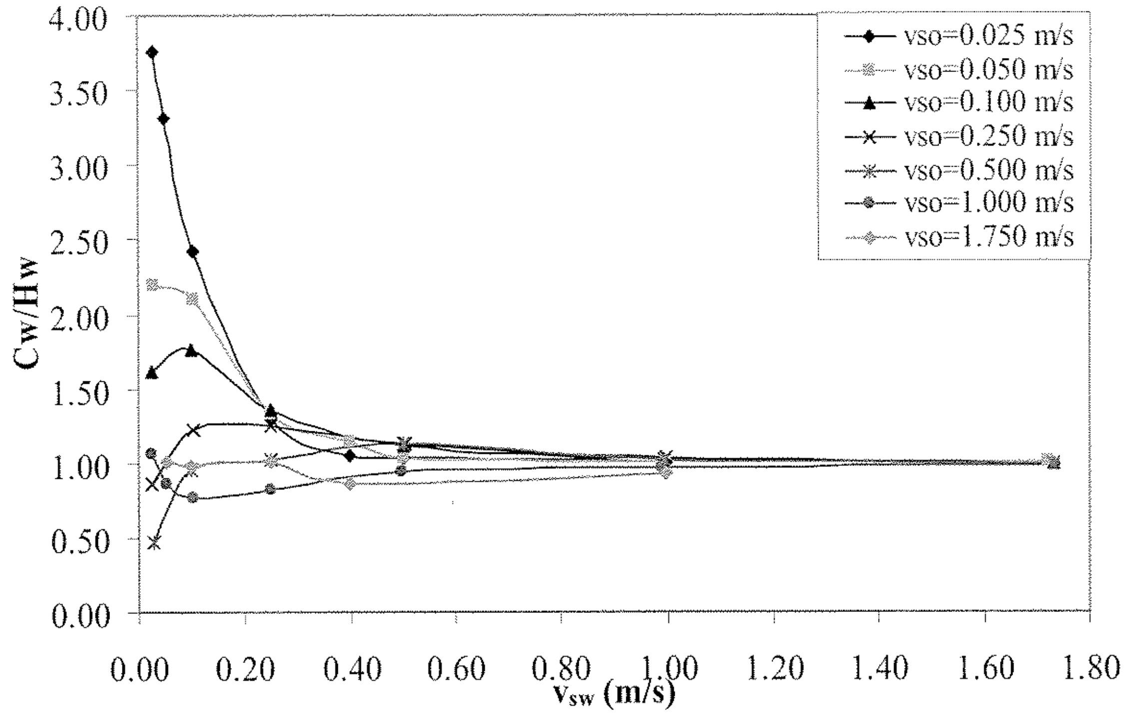

Figure 24: Experimental Water Holdup Ratio (-2° Downward)

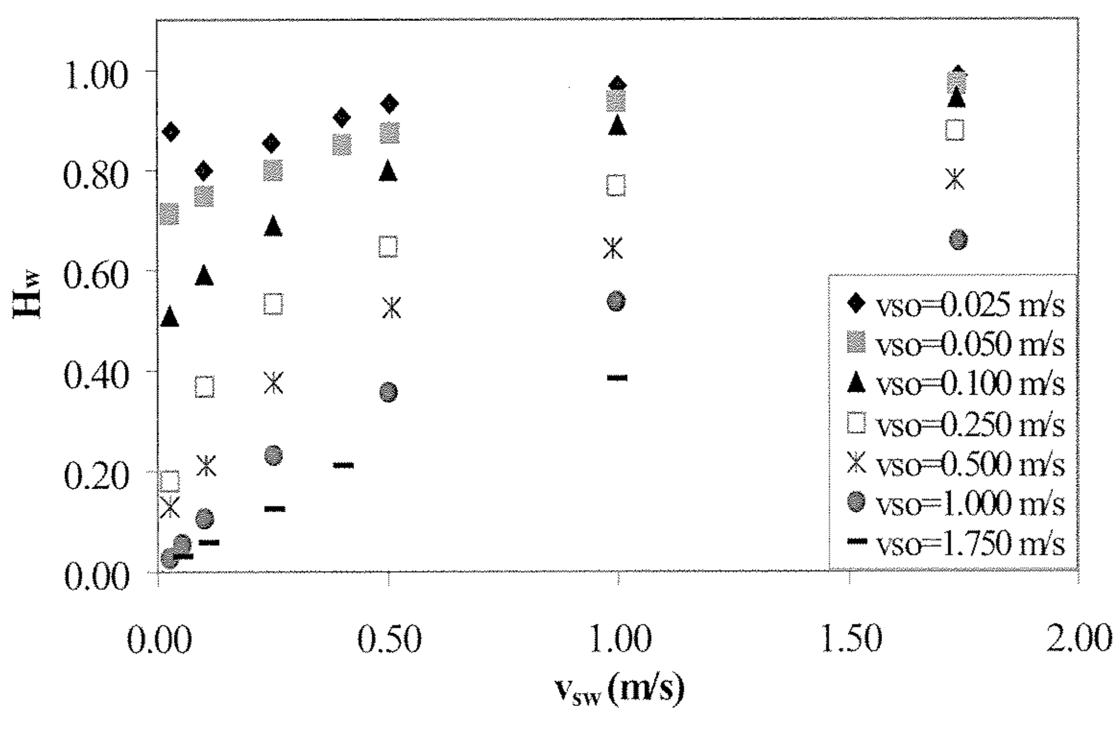

Figure 25: Experimental Water Holdup (+2° Upward)

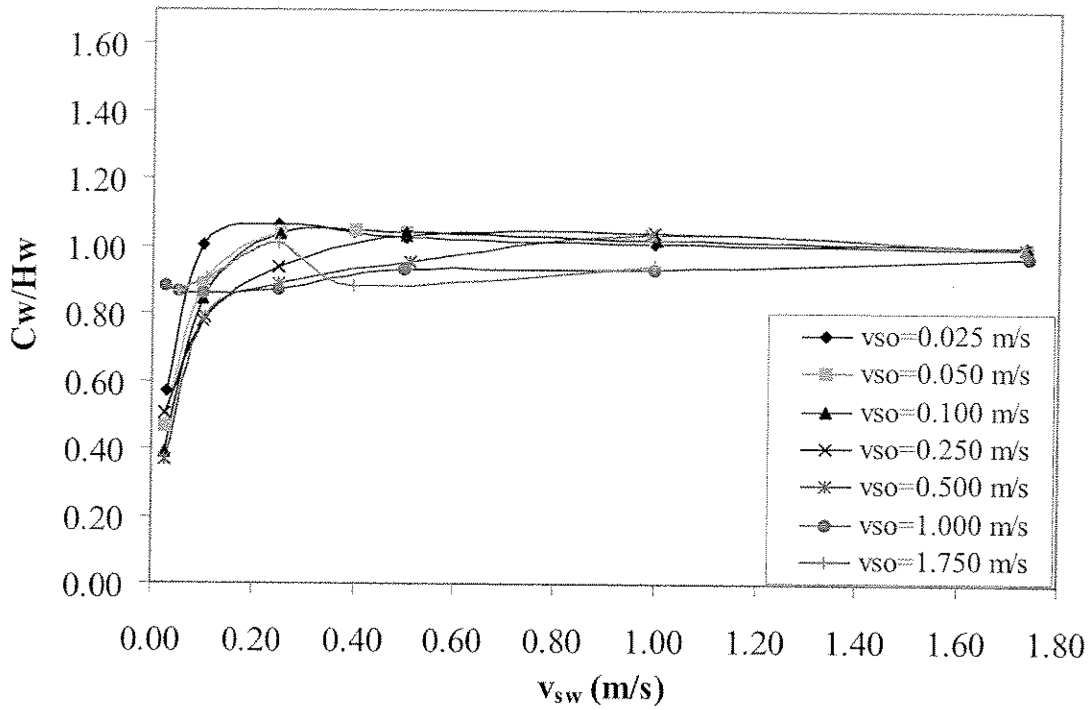

Figure 26: Experimental Water Holdup Ratio (+2° Upward)

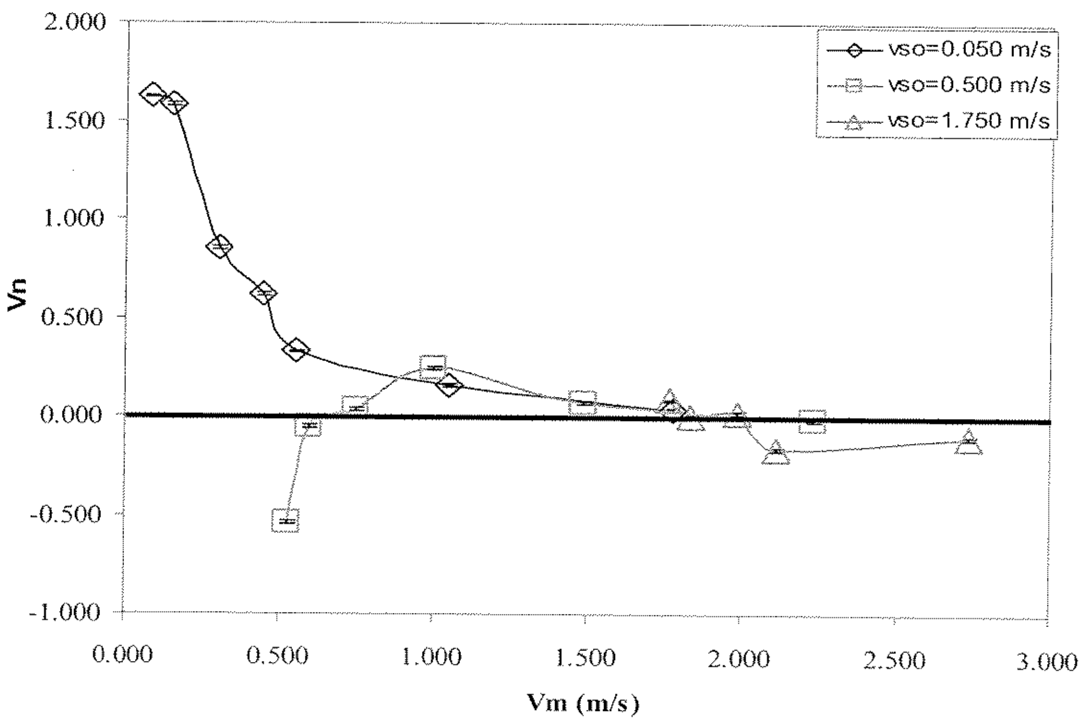

Figure 27: Normalized Drift Velocity (-2° Downward)

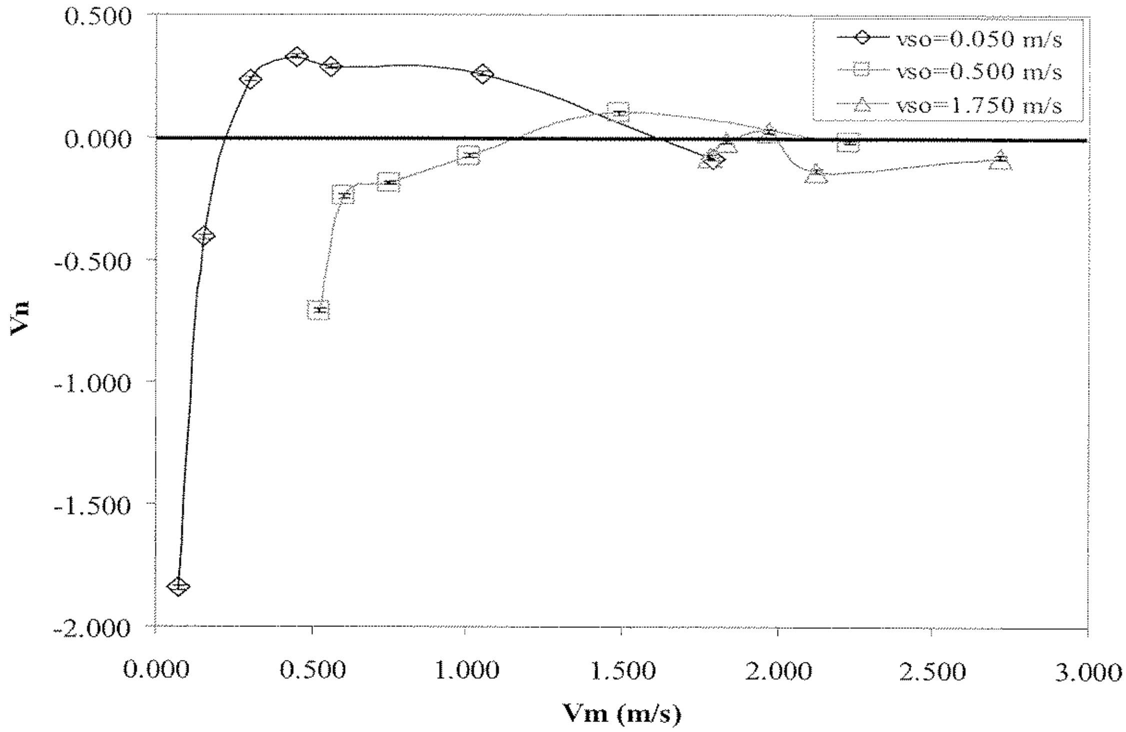

Figure 28: Normalized Drift Velocity (+2° Upward)

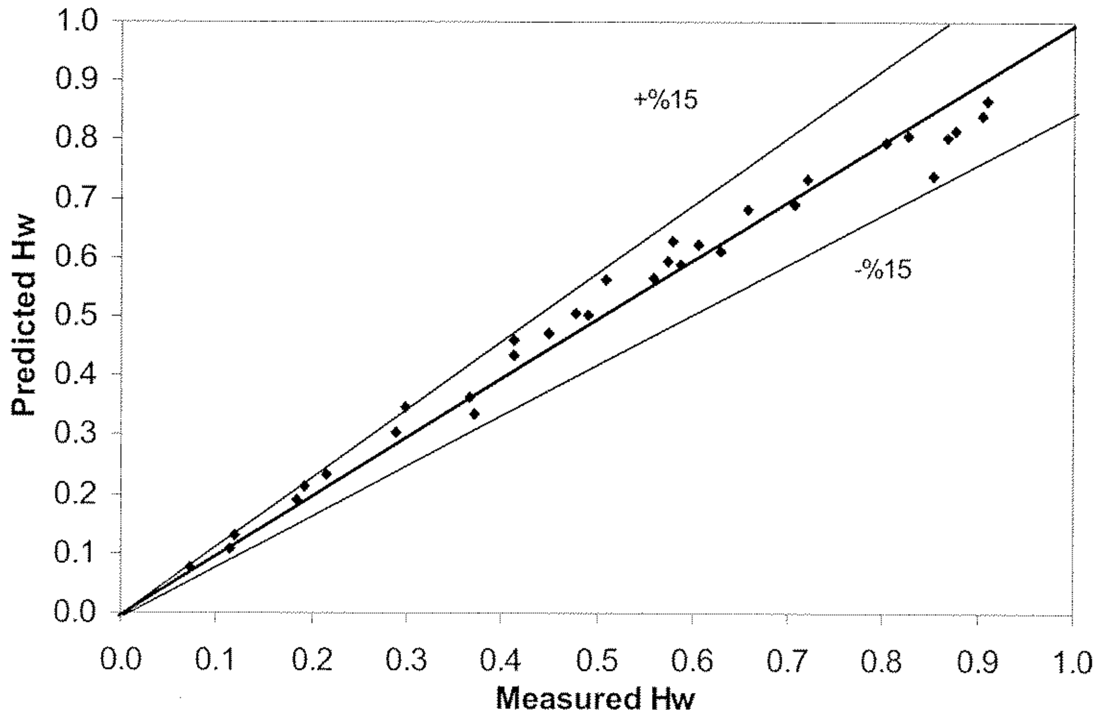

Figure 29: Unified Model Water Holdup Comparisons (+1° Upward)

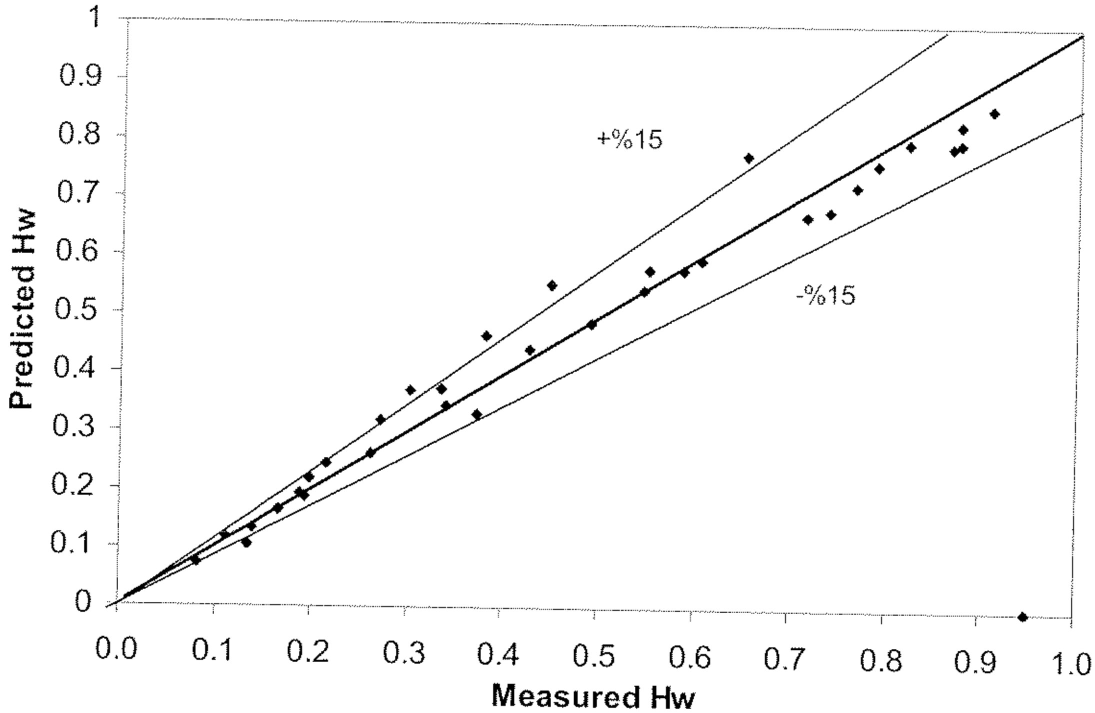

Figure 30: Unified Model Water Holdup Comparisons (-1° Downward)

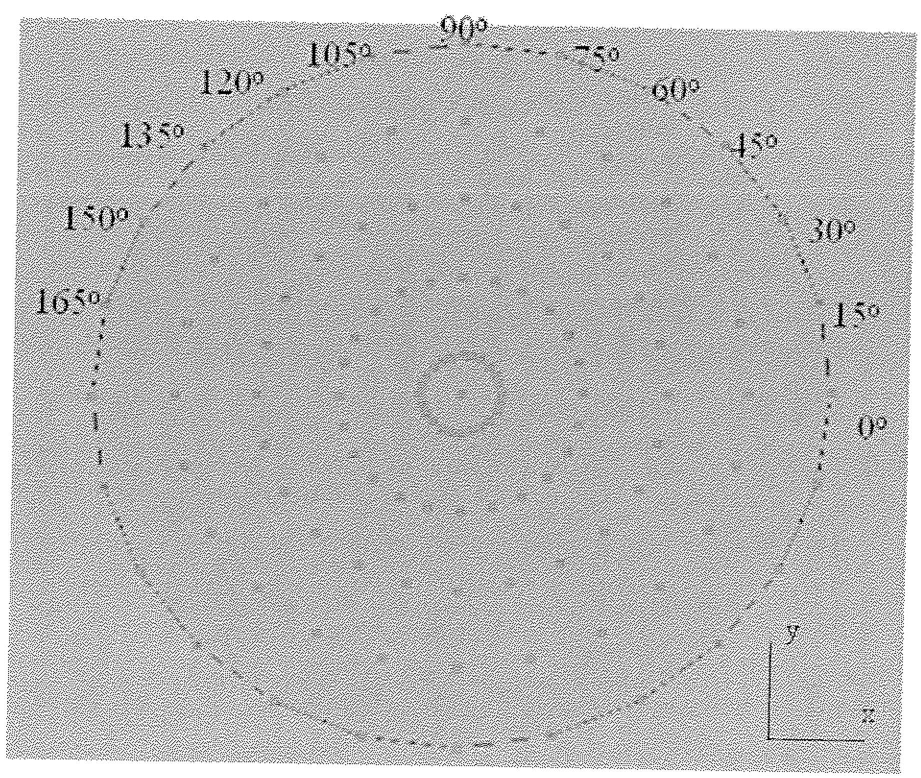

Figure 31: New Model for Phase Distribution

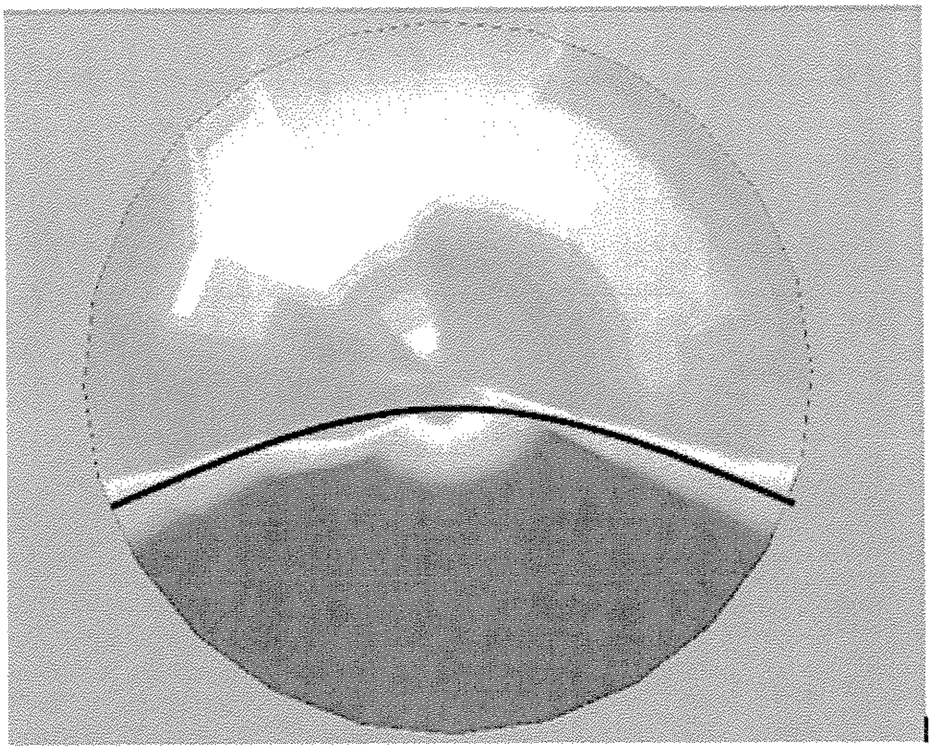

Figure 32: Phase Distribution for v_{so} = 0.050 m/s, v_{sw} = 0.050 m/s (-2° Downward)

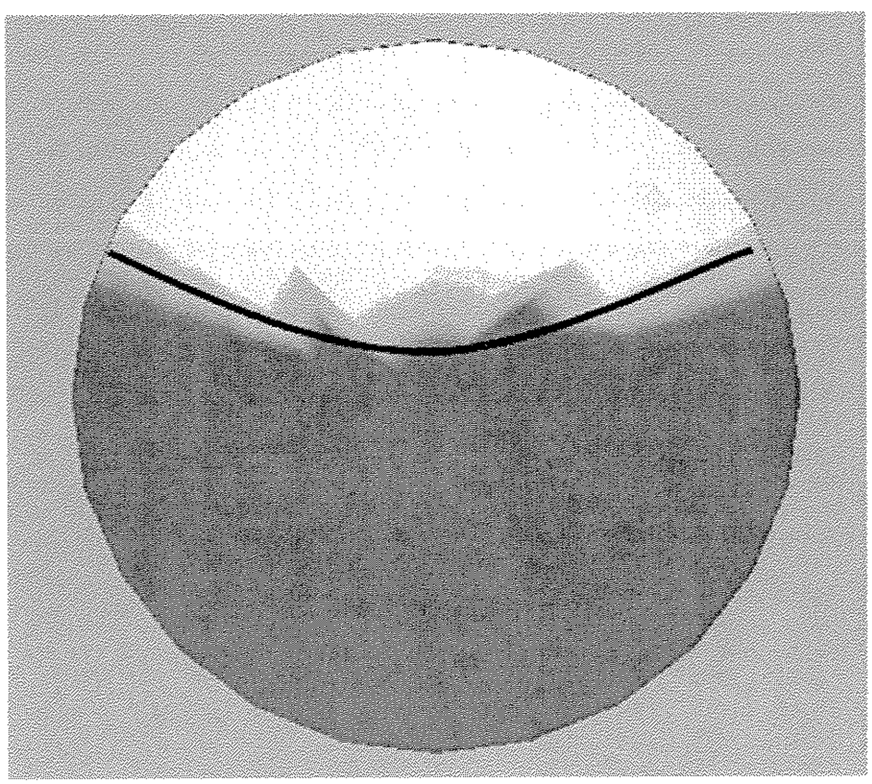

Figure 33: Phase Distribution for v_{so}=0.050 m/s, v_{sw}=0.050 m/s (+2° Upward)

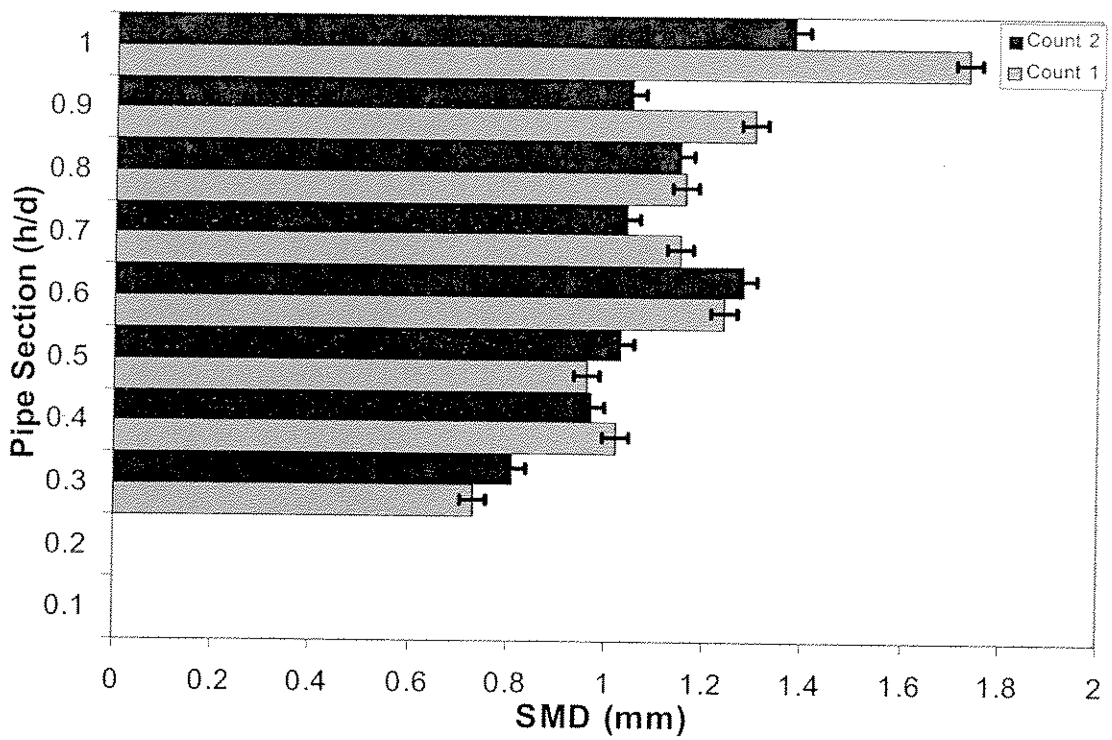

Figure 34: Repeatability of Counting Droplets

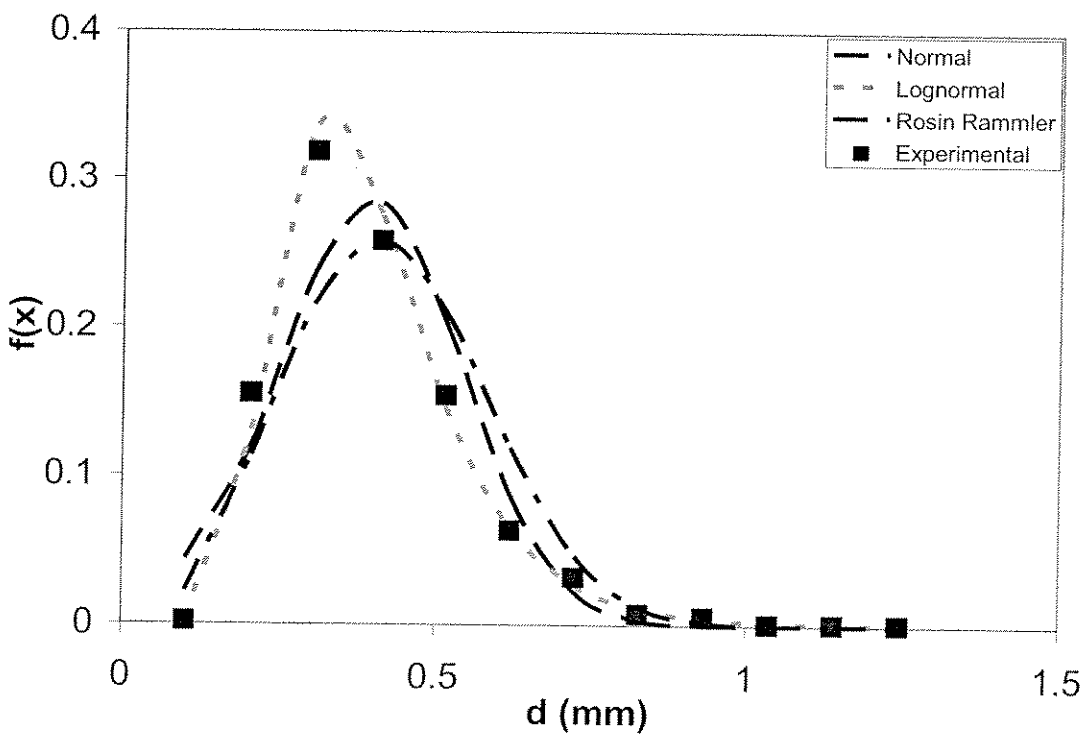

Figure 35: Droplet Size Distributions (v_{so}=0.025 m/s, v_{sw}=1.750 m/s, +2° Upward)

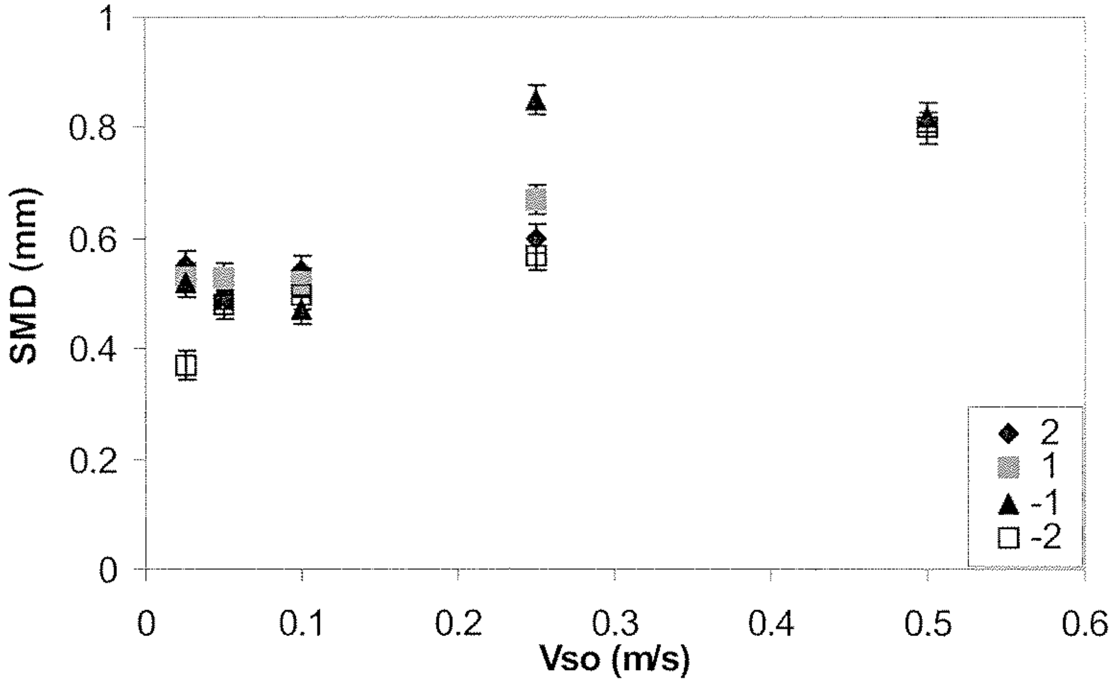

Figure 36: Variation of SMD with v_{so} and Inclination Angles for O/W Dispersions

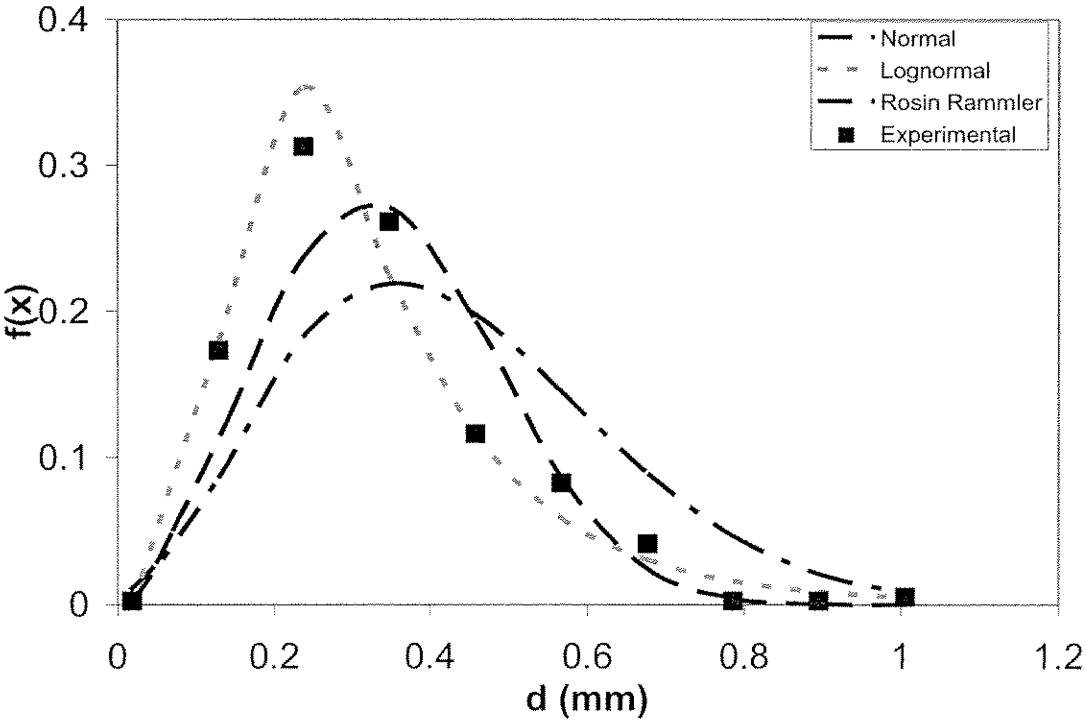

Figure 37: Droplet Size Distributions (v_s=1.750 m/s, v_{sw}=0.100 m/s, +2° Upward)

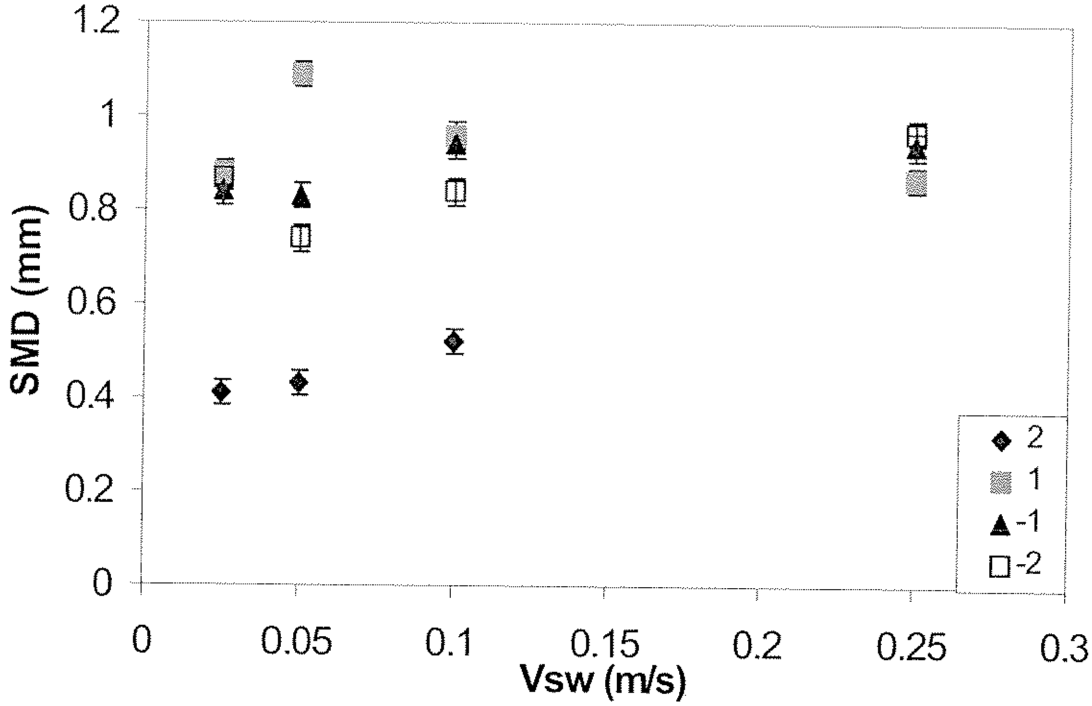

Figure 38: Variation of SMD with v_{sw} and Inclination Angles for W/O Dispersions

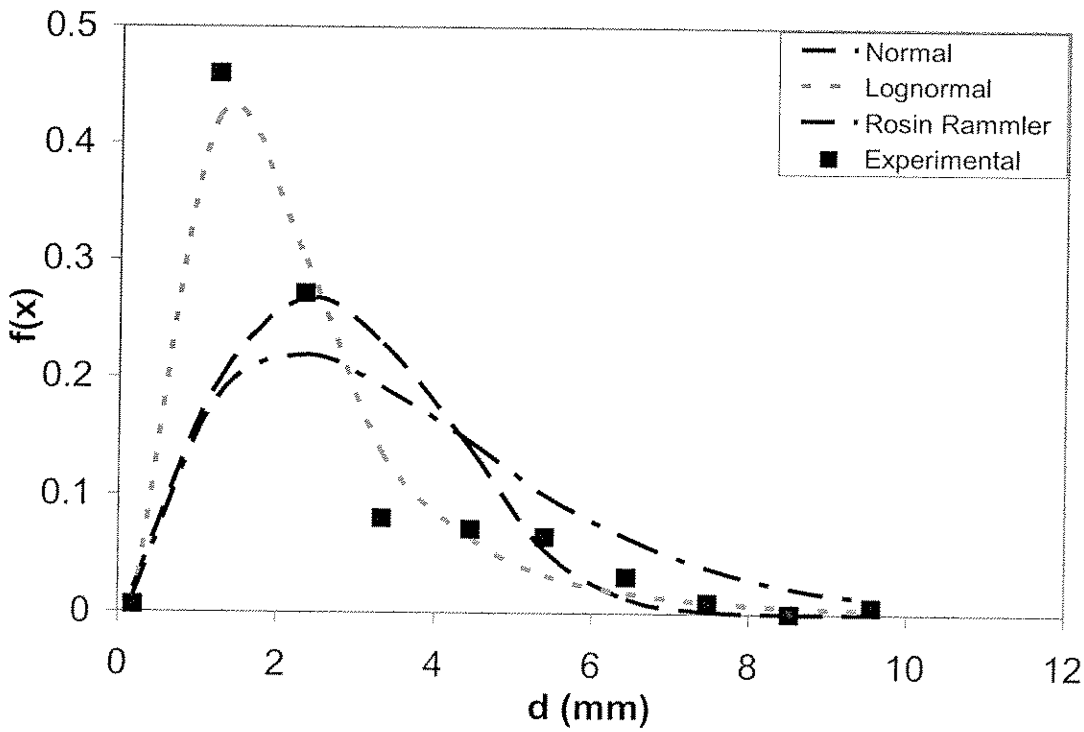

Figure 39: Droplet Size Distributions (v_{so}=0.500 m/s, v_{sw}=0.100 m/s, +2° Upward)

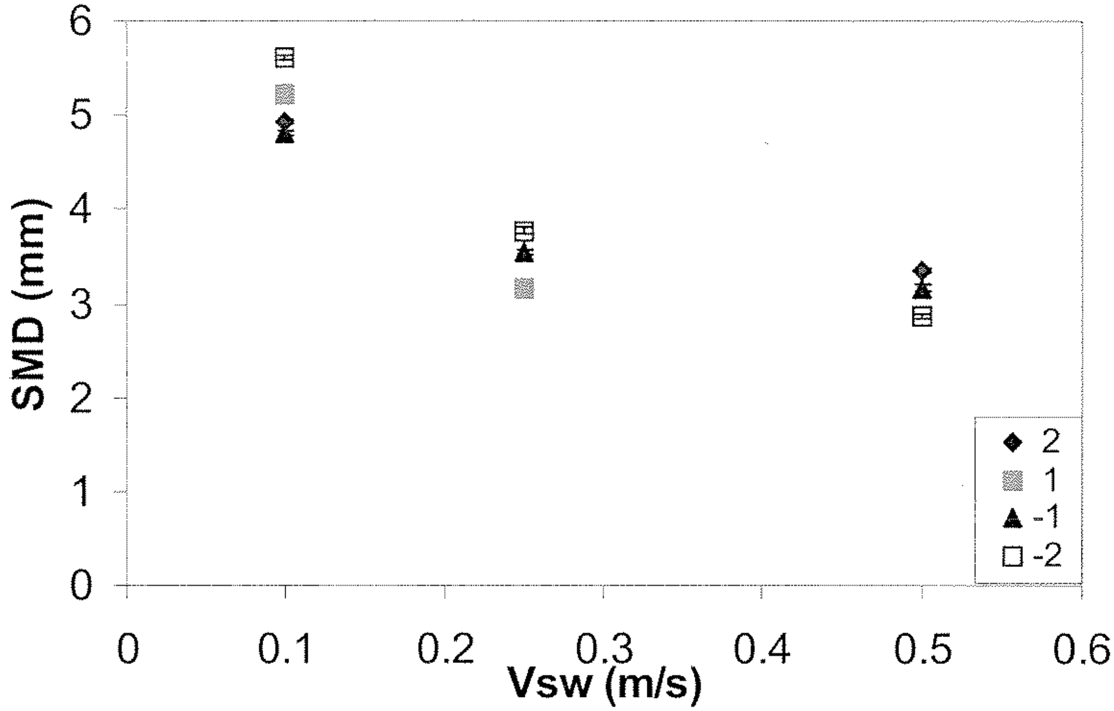

Figure 40: Variation of SMD with v_{sw} and Inclination Angles for ST&MI Dispersions

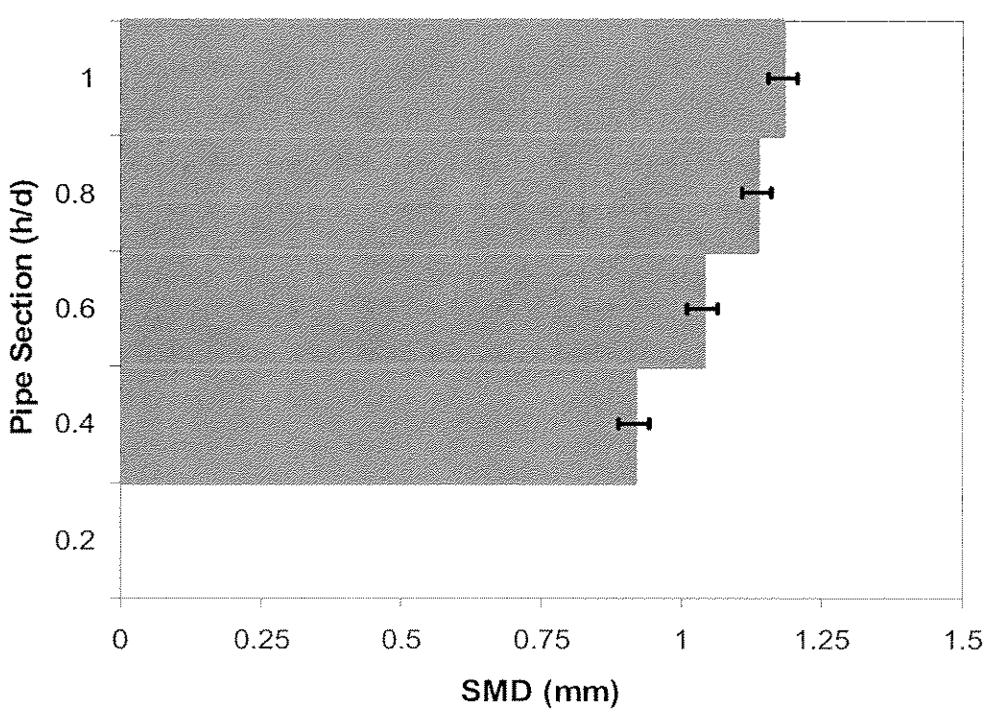

Figure 41: SMD vs. h/D for D O/W & W (v_{so}=0.050 m/s, v_{sw}=1.000 m/s, +2° Upward)

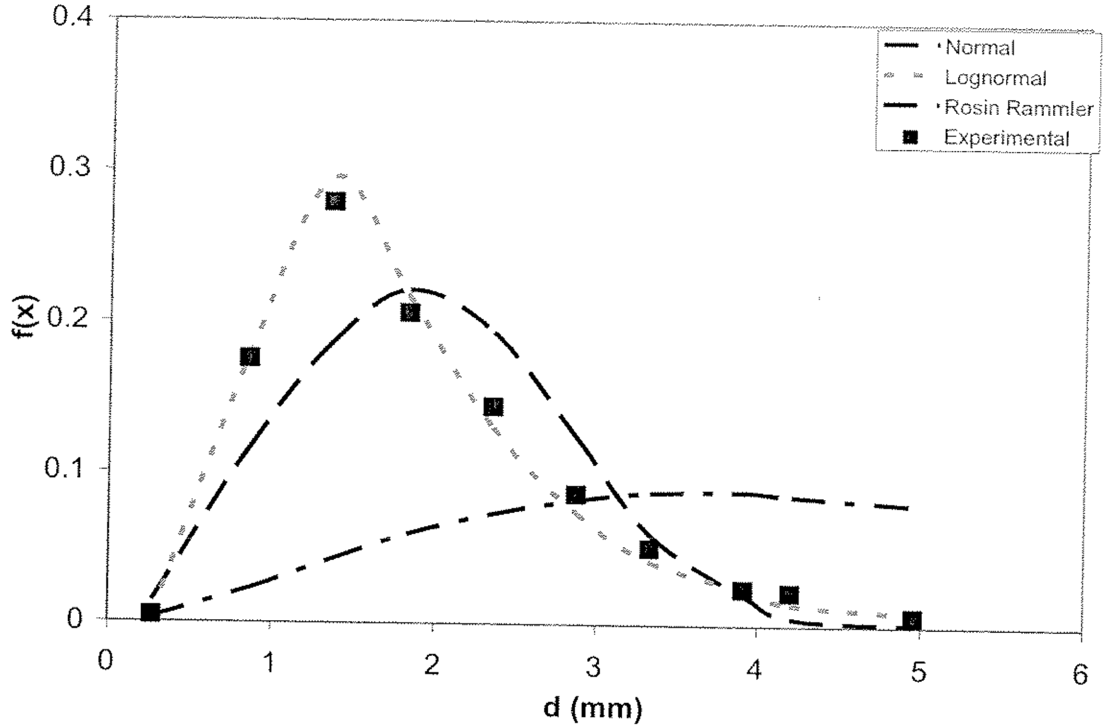

Figure 42: Oil Droplet Size Distributions (v_{so}=1.000 m/s, v_{sw}=0.500 m/s, -1° Downward)

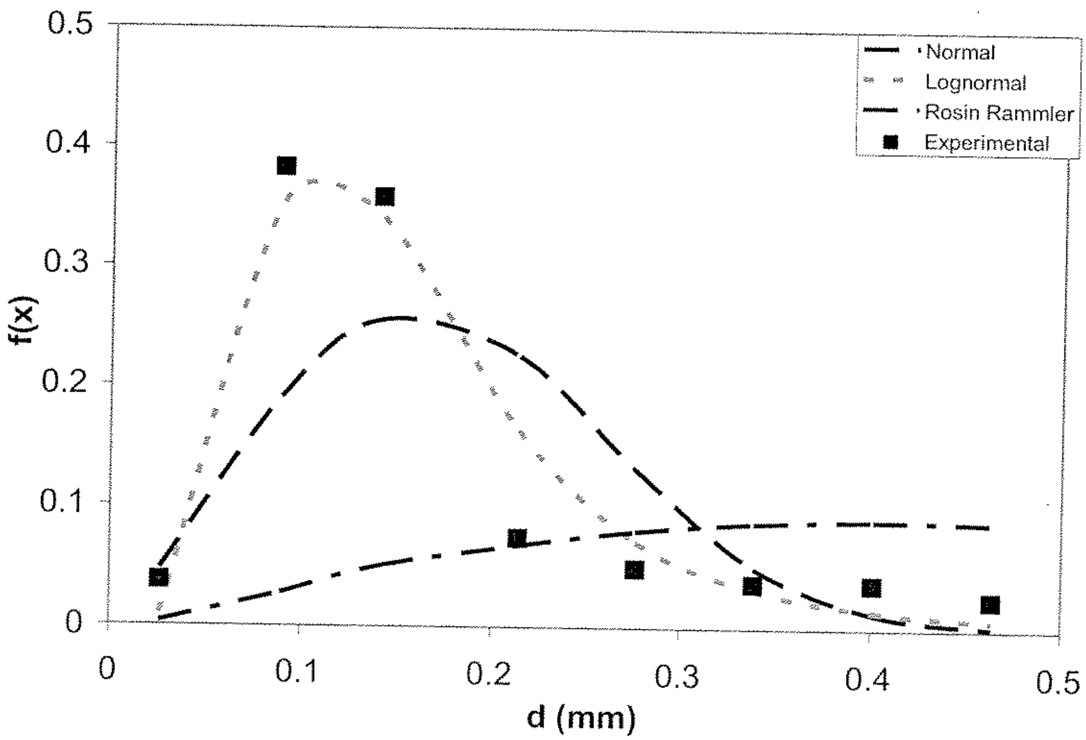

Figure 43: Water Droplet Size Distribution (v_{so}=1.000 m/s, v_{sw}=0.500 m/s, -1° Downward)

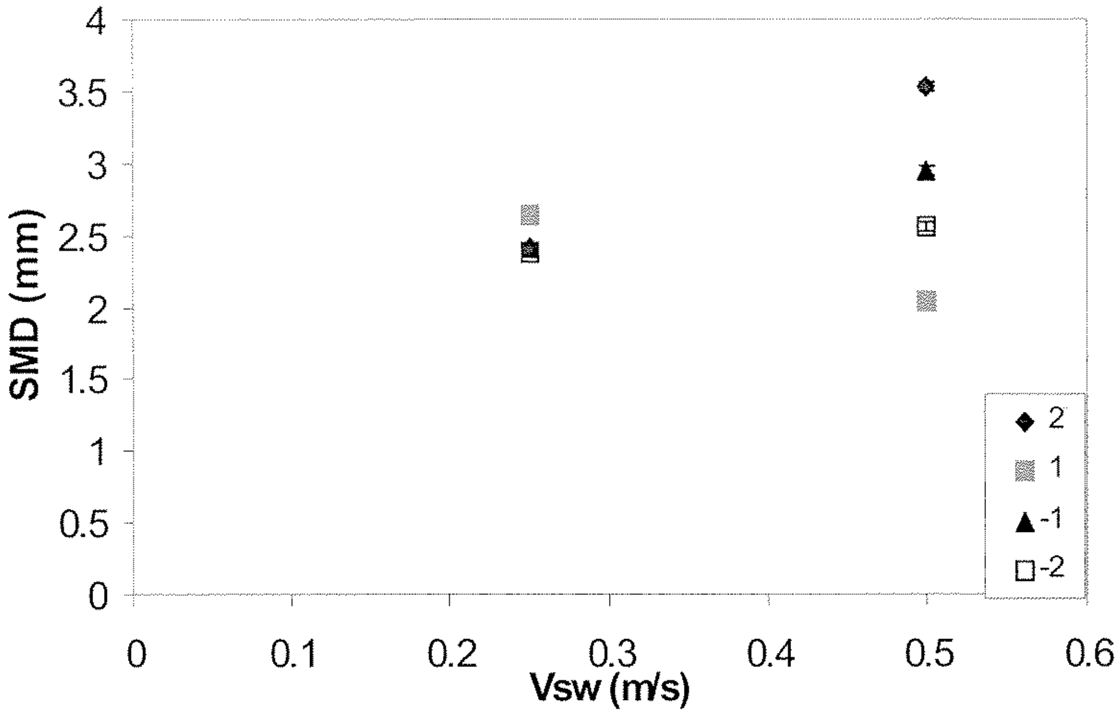

Figure 44: Variation of SMD with v_{sw} and Inclination Angles for Oil Droplets

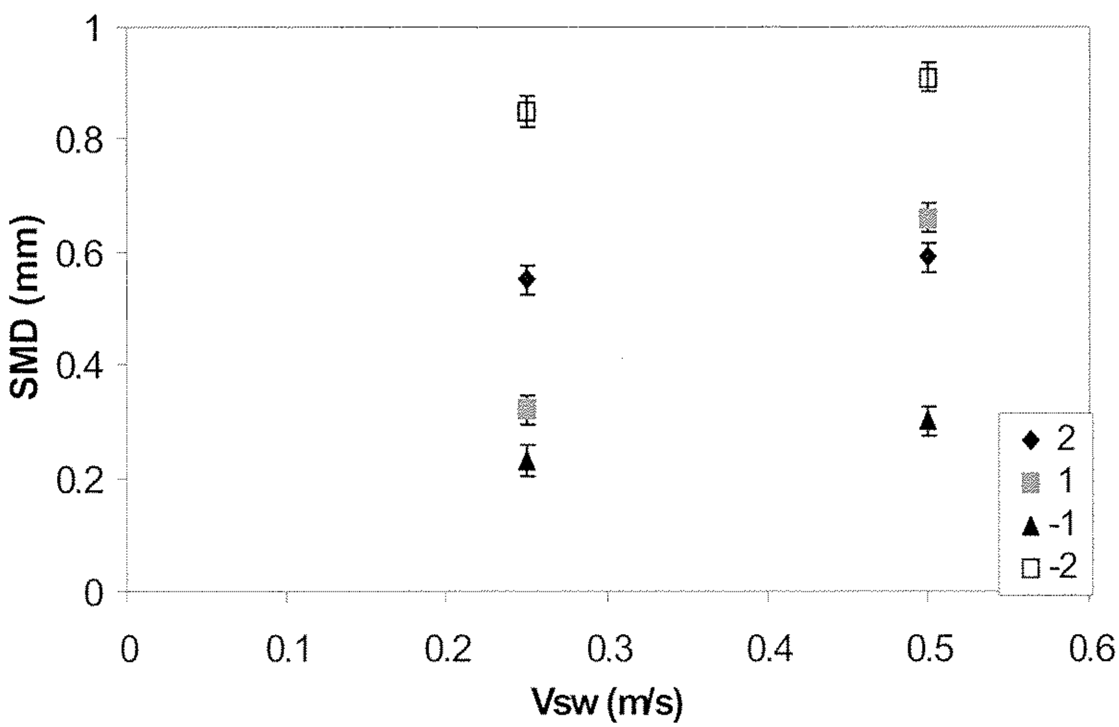

Figure 45: Variation of SMD with v_{sw} and Inclination Angles for Water Droplets

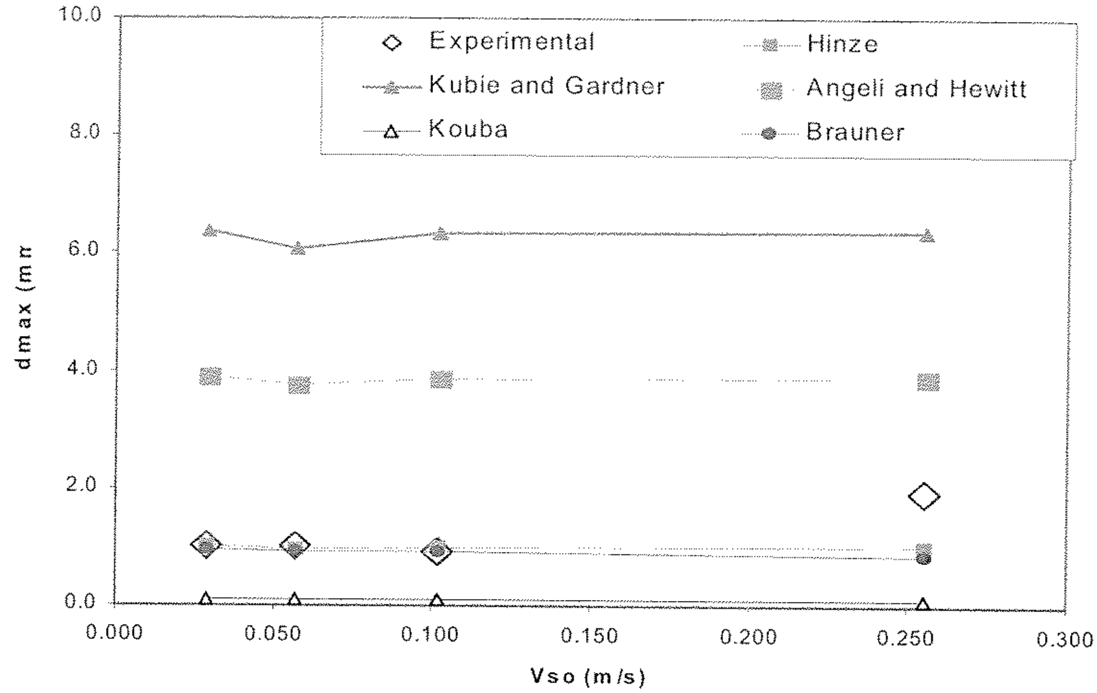

Figure 46: Maximum Diameter Comparisons for v_{sw}=1.750 m/s (-1° Downward)

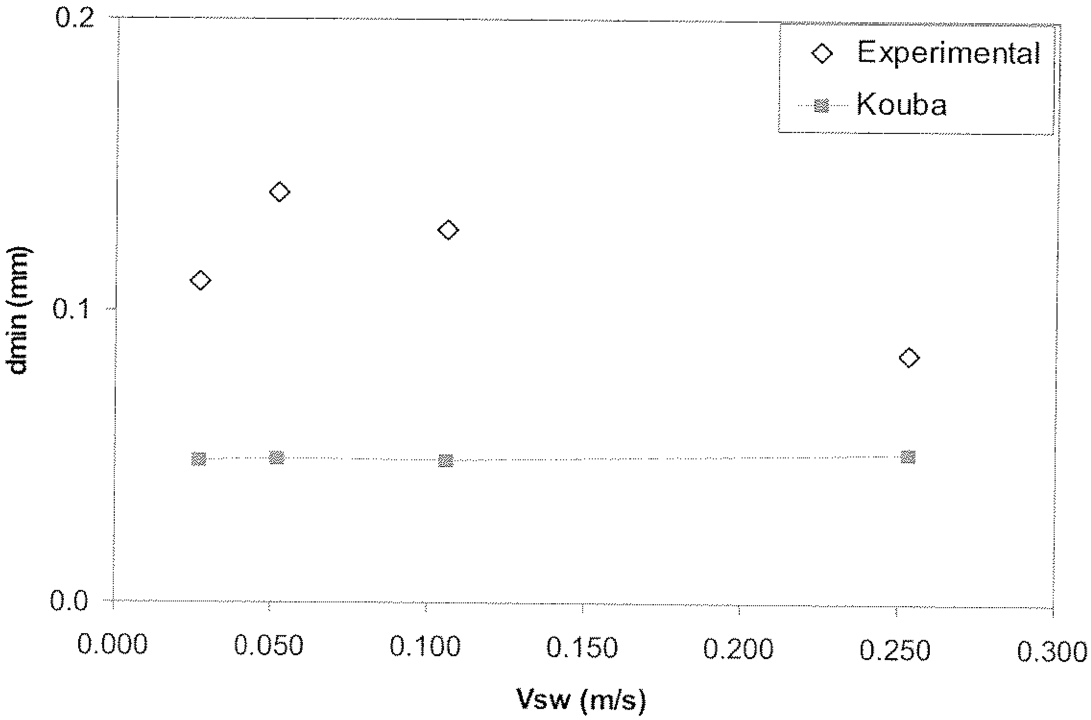

Figure 47: Minimum Diameter Comparisons for v_{sw}=1.750 m/s (-1° Downward)

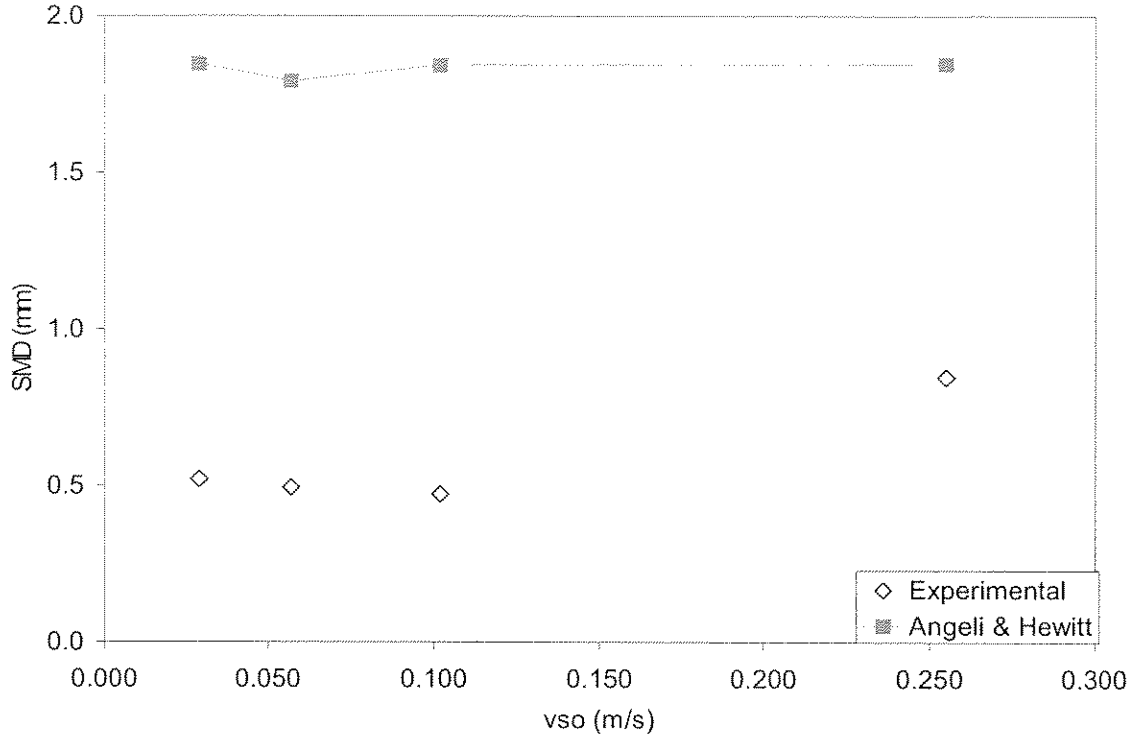

Figure 48: SMD Comparisons for v_{sw}=1.750 m/s (-1° Downward)

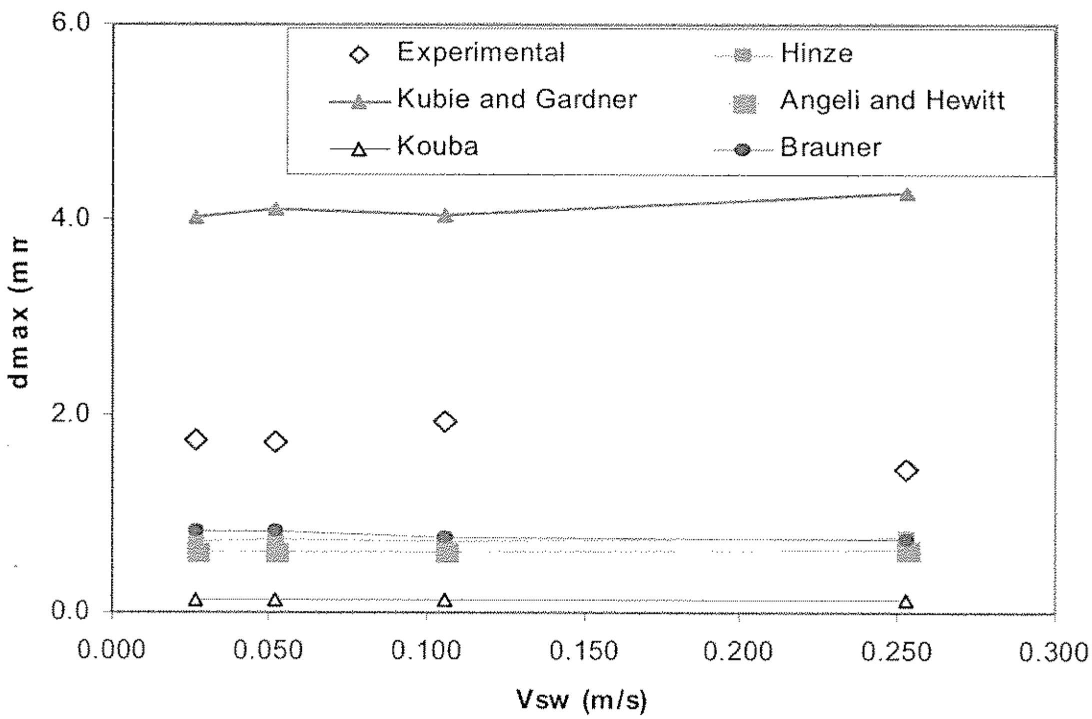

Figure 49: Maximum Diameter Comparisons for v_{so}=1.750 m/s (-1° Downward)

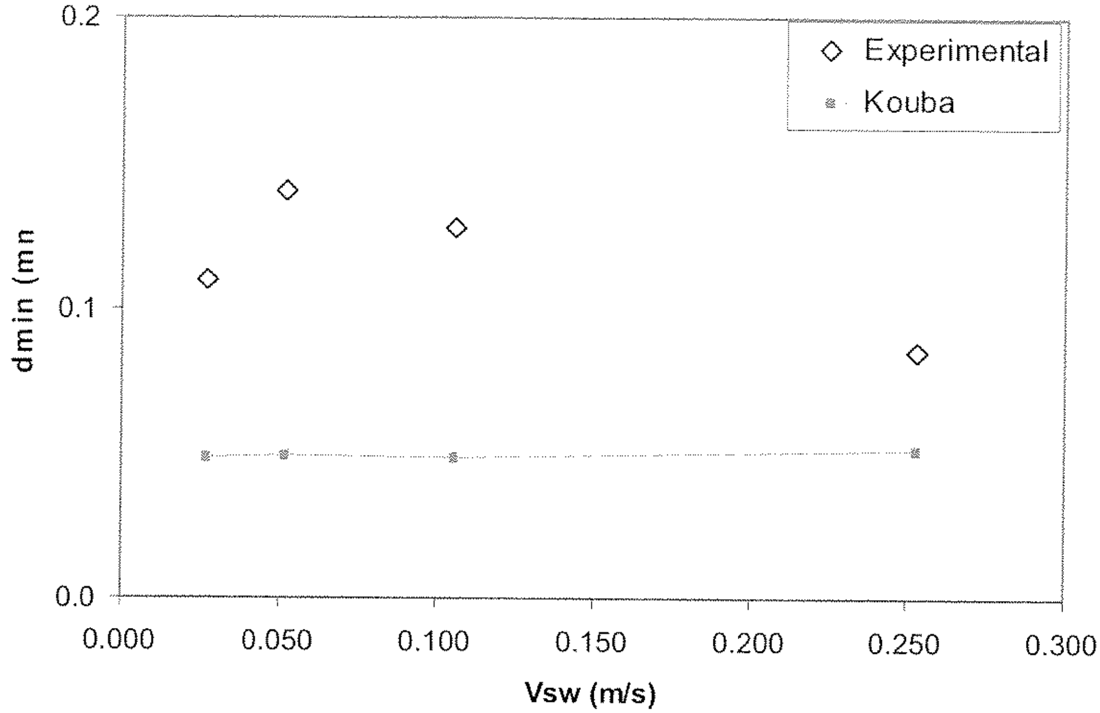

Figure 50: Minimum Diameter Comparisons for v_{so}=1.750 m/s (-1° Downward)

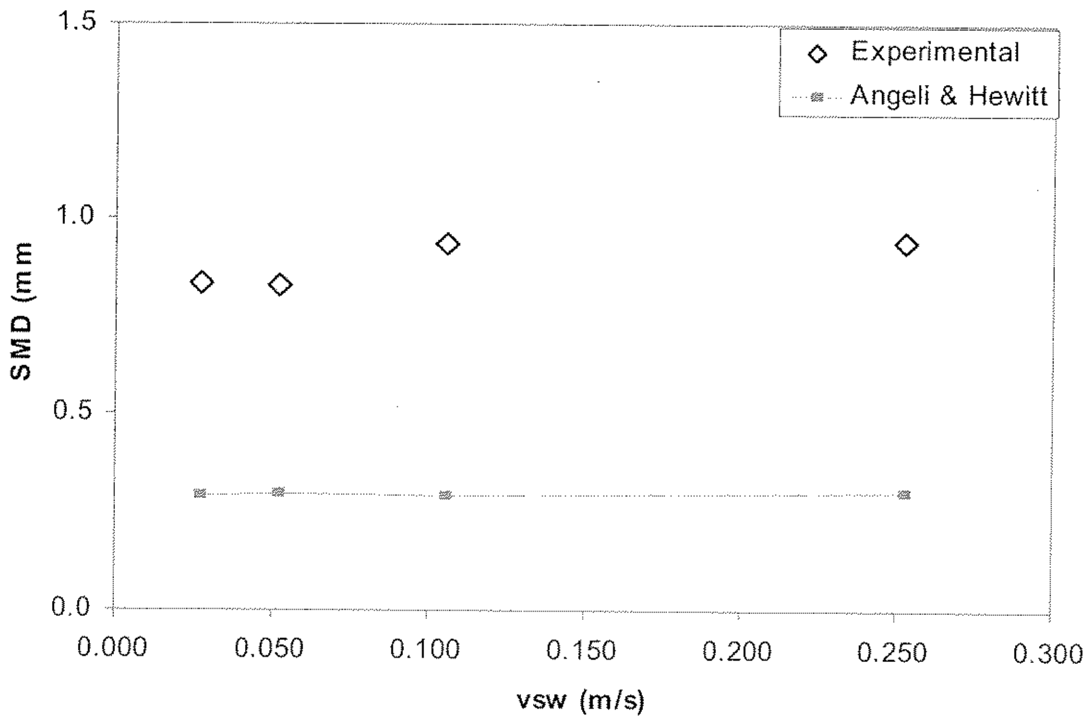

Figure 51: SMD Comparisons for v_{so}=1.750 m/s (-1° Downward)

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Fluid Flow Projects

Lagrangian-Eulerian Transient Two-Phase Flow Model

Kwon Il Choi

Advisory Board Meeting, November 06, 2007

Outline

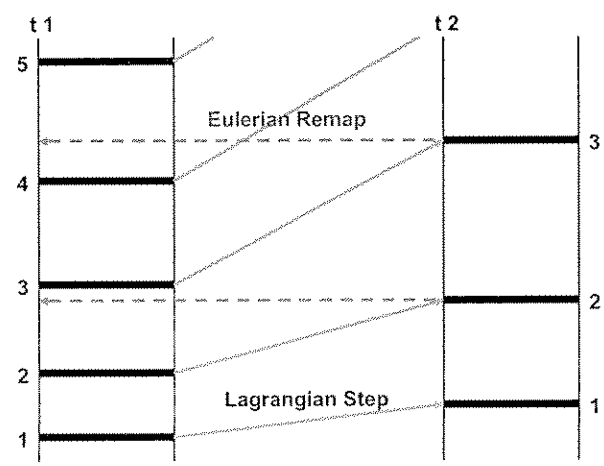
- Objectives
- Computational Model Development
- Simulation of Test Cases
- Project Schedule

Objectives

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

Fluid Flow Projects Advisory Board Meeting, November 06, 2007

Computational Methodology

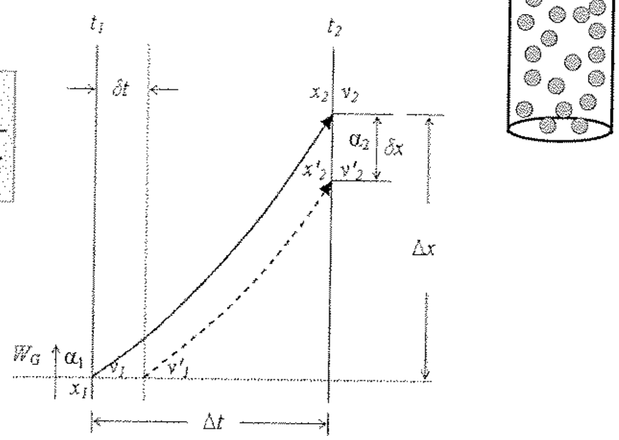


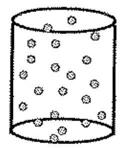
Fluid Flow Projects Advisory Board Meeting, November 06, 2007

Transient Modeling

Gas Mass Balance

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





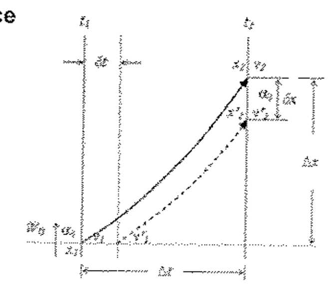
Fluid Flow Projects

Advisory Board Meeting, November 06, 2007

Transient Modeling ...

Gas Mass Balance

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



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

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

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

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

Fluid Flow Projects

Advisory Board Meeting, November 06, 2007

Transient Modeling …

Gas Mass Balance

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

$$\frac{Dv}{Dt} = \frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x}$$

$$\frac{\partial v_2}{\partial x} = \frac{1}{v_2}\left(\frac{v_2 - v_1}{\Delta t} - \frac{\partial v_2}{\partial t}\right)$$

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

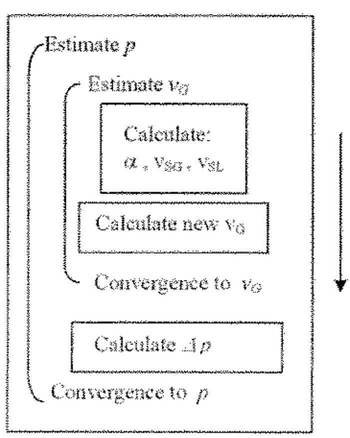
Steady State

$$\alpha_{2ss} = \frac{W_G}{\rho_G(x_2)\,A_p\,v_2}$$

Transient Modeling …

Numerical Solution Strategy

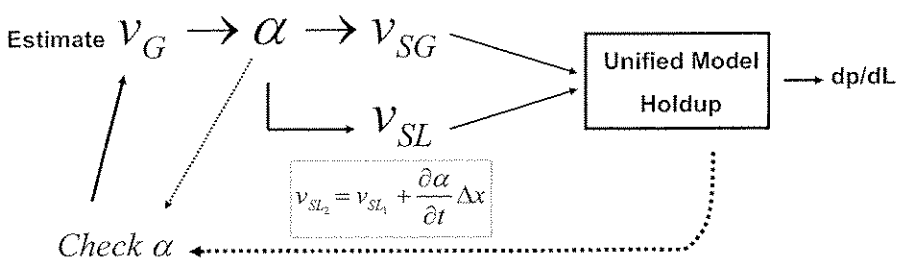
For 1 Cell



Transient Modeling ...

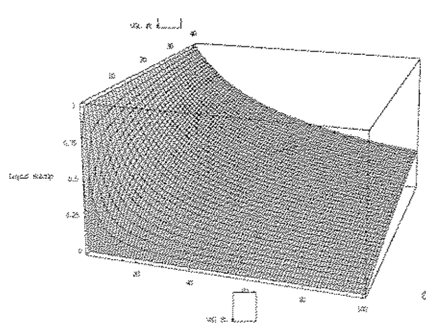
Coupling with Unified SS Model

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

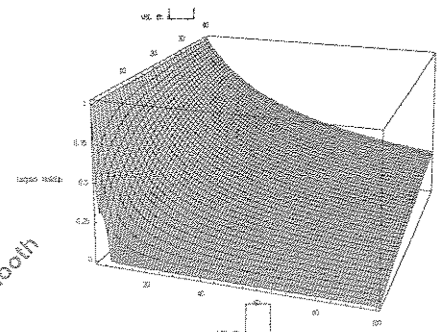


Unified Model in Table

Holdup vs. V_{SL} vs. V_{SG}



Smooth

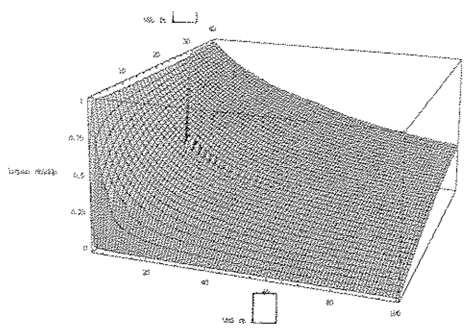


Horizontal

Vertical

Example of Discontinuous Table

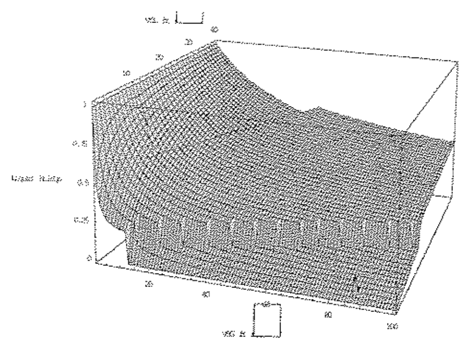
Holdup vs. V_{SL} vs. V_{SG}



Horizontal

(Petalas & Aziz)

Not Smooth



Vertical

(Kaya)

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Unified Model in Table

Interpolation parameters:

1. Diameter : 2 – 6 inches
2. Angle : -90 to +90 degrees
3. Liquid Density : 40 to 70 lb/ft^3
4. Gas Density : 0.01 to 35 lb/ft^3
5. V_{SL} : 0.01 to 80 ft/s
6. V_{SG} : 0.01 to 200 ft/s

Over 4.5 million points

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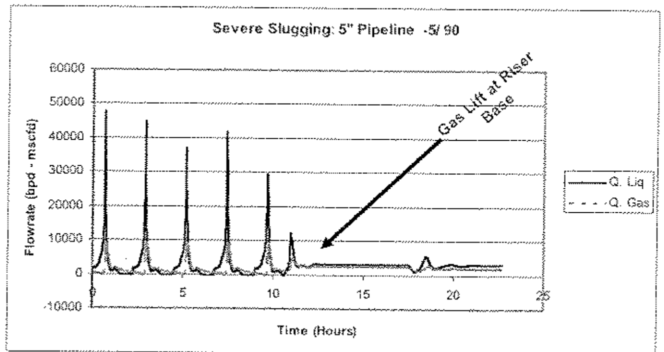
Experimental Study

- Severe Slugging
  - Demonstration



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Project Schedule

- Model Validation January 2008
- Final Report May 2008

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Lagrangian-Eulerian Transient Two-Phase Flow Model

Kwon Il Choi

PROJECTED COMPLETION DATES:

Model Validation.. January 2008
Final Report.. May 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's 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

$$\alpha = \frac{m_G}{\bar{\rho}_G A_p \delta x}, \qquad (1)$$

where $\bar{\rho}_G$ 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.

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

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.

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

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

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

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.

$$\bar{\rho}_G = \frac{1}{\delta x}\int_{x_2-\delta x}^{x_2} \rho_G\,dx, \qquad (5)$$

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

$$\bar{\rho}_G = \rho_{G2} + \frac{1}{2}\left.\frac{\partial \rho_G}{\partial x}\right|_{x_2} \delta x. \qquad (7)$$

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

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

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

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,

$$v_{G1}' = v_{G1} + \frac{\partial v_{G1}}{\partial t}\delta t, \qquad (10)$$

$$v_{G2}' = v_{G2} - \frac{\partial v_{G2}}{\partial x}\delta x. \qquad (11)$$

Finally, the small length δx is given by

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

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,

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

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:

1. Inclination angle

2. Diameter
3. Superficial gas velocity
4. Superficial liquid velocity
5. Gas density
6. Liquid density
7. Gas viscosity
8. Liquid viscosity
9. Roughness
10. 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 one fast computer available.

Fig. 3 and Fig. 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 done 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. 2. 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 done to calculate the new estimate of pressure. The whole procedure is repeated until convergence is reached on the value of pressure p.

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. Flowline of 5" inside diameter, 10000 ft long with an inclination angle of -5.0 degrees
2. Riser of 5" inside diameter, 5987.5 ft long with an inclination angle of 90 degrees
3. Liquid input of constant 2000 stb/d
4. Gas input of constant 1000 mscf/d
5. Fluids are water and natural gas

Fig. 5 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 reduecd to 500 mscf/d which still keeps the system stable with a small oscilation.

Future Works

1. Comparison with experimental test.
2. Final report.

References

1. Beltran, Carlos A. "Severe Slugging Prediction for Gas-Oil-Water Flow in Pipeline-Riser Systems," Ms.C. Thesis, The University of Tulsa, 2005

2. Fedkiw, R. P.: "Coupling an Eulerian Fluid Calculation to a Lagrangian Solid Calculation with the Ghost Fluid Method," Computer Science Department, Stanford University, Stanford, California, 2001

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

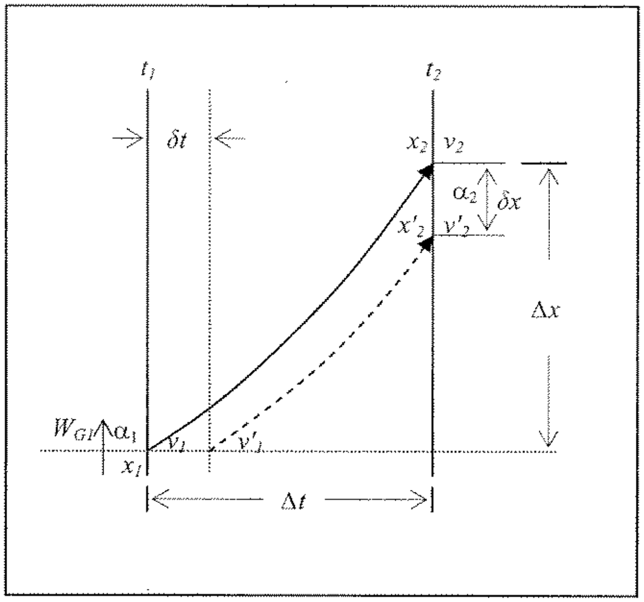

Figure 1 – Schematic of gas mass balance

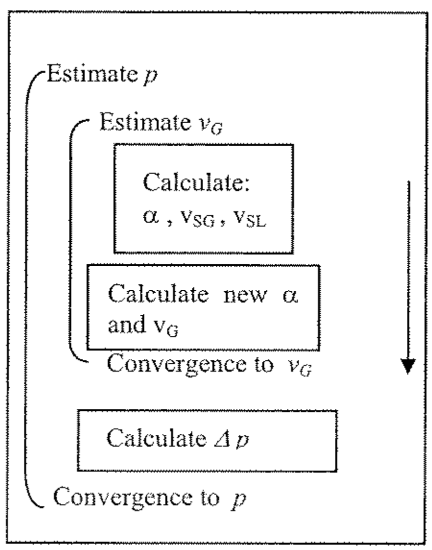

Figure 2 – Numerical solution diagram

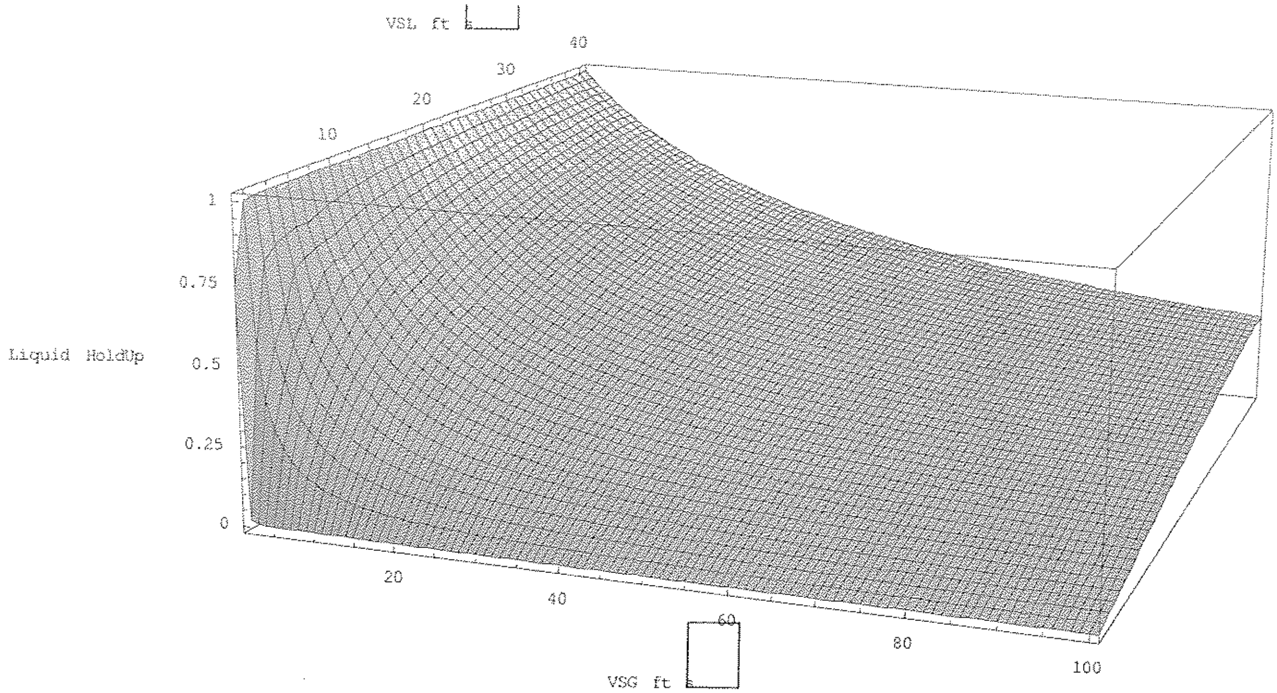

Figure 3 – Plot of liquid holdup table for horizontal flow based on Unified model.

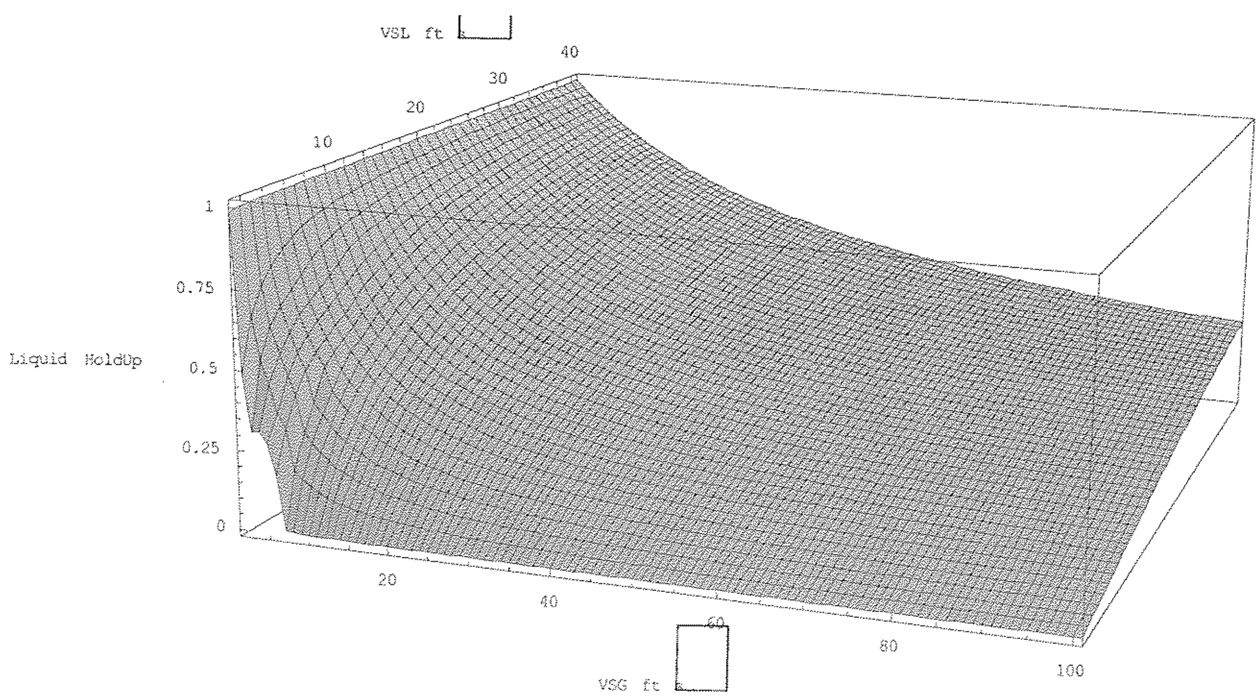

Figure 4 – Plot of liquid holdup table for vertical flow based on Unified model.

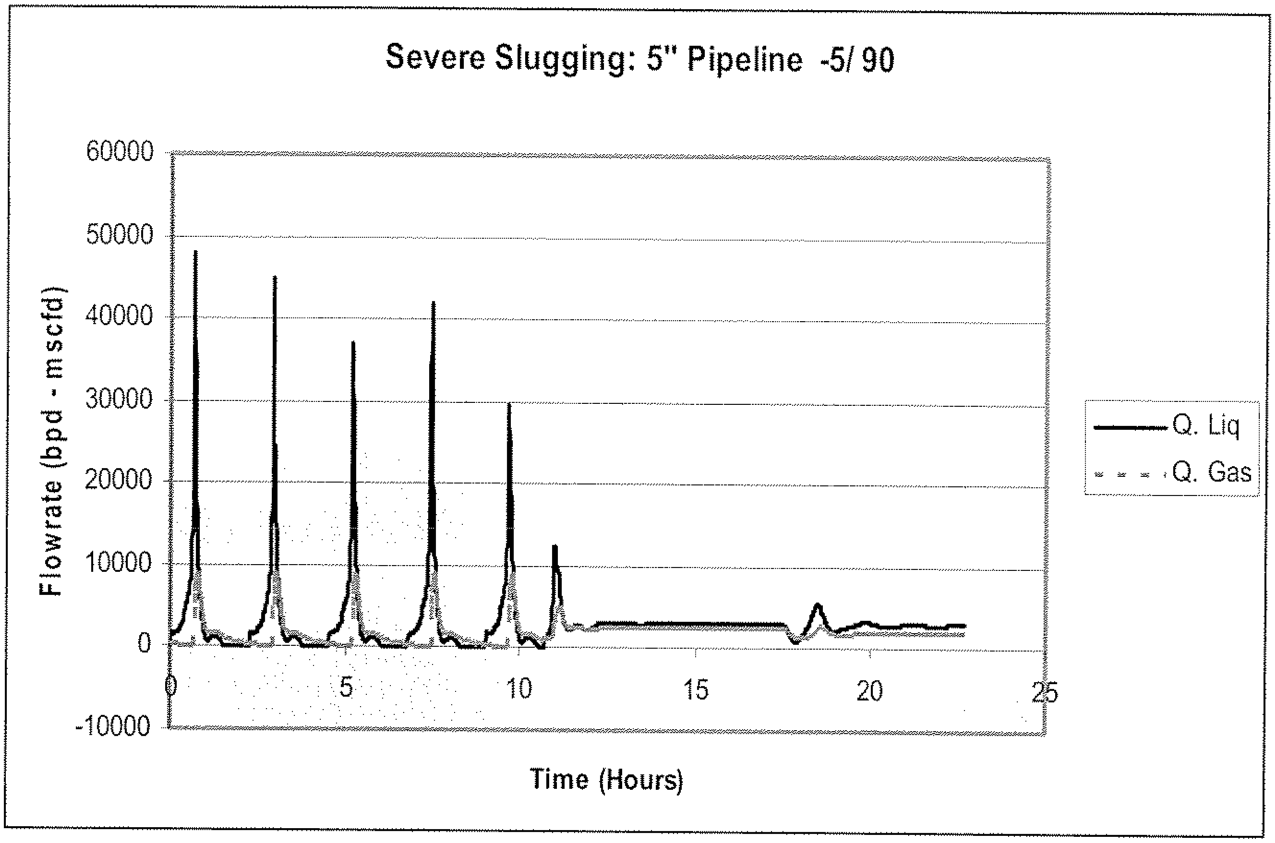

Figure 5 – Severe slugging simulation for 5 inch pipeline with -5 degree flowline and 90 degree riser.

Fluid Flow Projects

An Experimental Study of Low Liquid Loading Gas-Oil-Water Flow in Horizontal Pipes

Hongkun (Tom) Dong

3Ø flow
Larger Diameter

Advisory Board Meeting, November 6, 2007

Outline

- Objectives
- Introduction
- Experimental Study
  - Facilities
  - Instrumentations
  - Tests
  - Results
- Model Evaluation
- Conclusions

Objectives

- Acquire Experimental Data of Low Liquid Loading Gas-oil-water Flow in Horizontal Pipes
- Compare with Gas-liquid Flow Experimental Data
- Compare with Model Predictions and Suggest Modifications or Develop New Model if Necessary

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Introduction

- Definition

Liquid Loading: Q_L/Q_G

Low Liquid Loading: ≤ 1100 $m^3/MMsm^3$

Wet Gas: Gas, Condensate Oil, Water

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Introduction ...

- Significance
  - Increase Gas Production
  - Problems Due to Water Presence
    - Pressure Drop Increase
    - Hydrates Formation
    - Corrosion
    - ...

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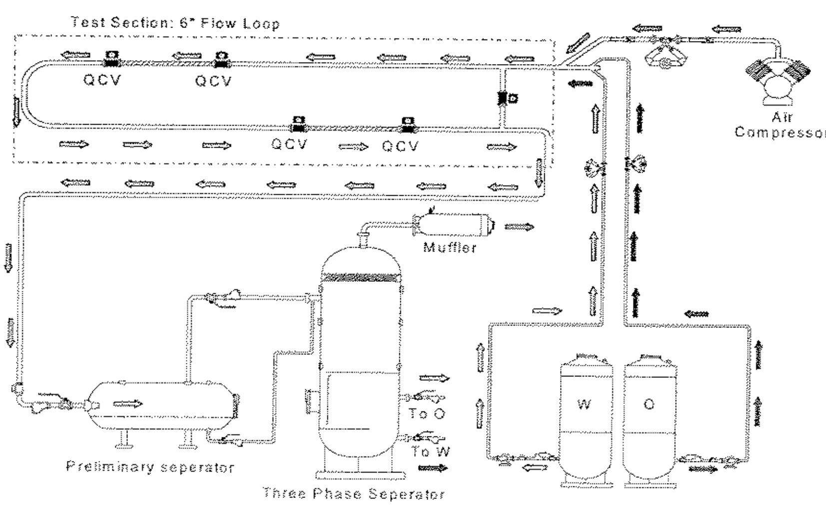
Schematic of Flow Loop



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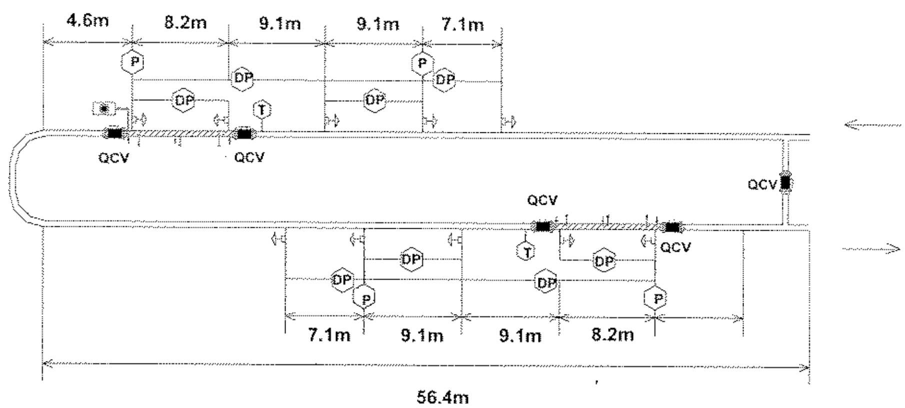
Schematic of Test Section



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Instrumentation

- Pressure: PTs & DPs
- Temperature: TTs
- Holdup: QCVs and Pigging System
- Wet Perimeter: Grades Inside Pipe
- Film Thickness: Conductivity Probes
- Liquid Velocity: Cold Liquid Injection
- Liquid Entrainment: Iso-kinetic Sampling System
- Cross-sectional Viewing System

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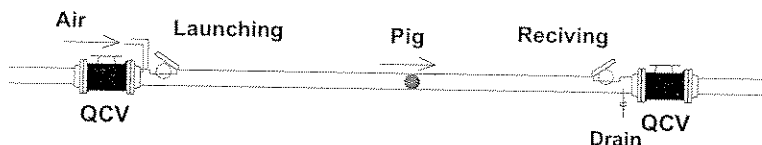
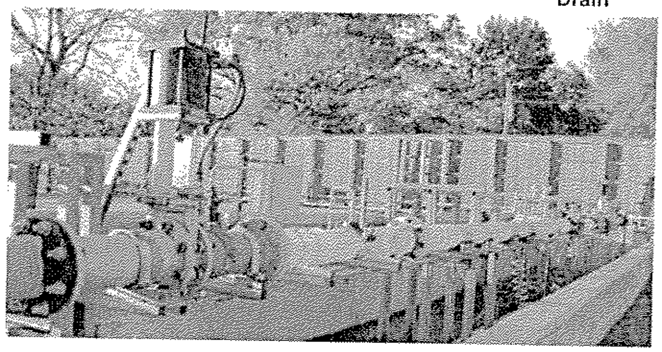
Holdups: QCVs & Pigging System





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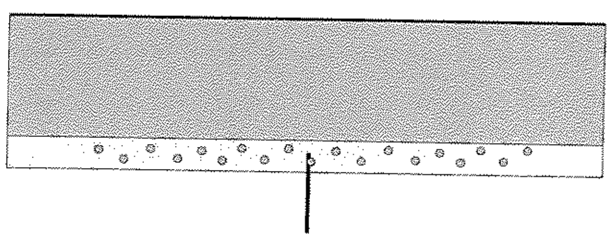
Film Thickness & Phase Continuity: Conductivity Probes

- Principle: Conductivity Difference
- Traverse across pipe



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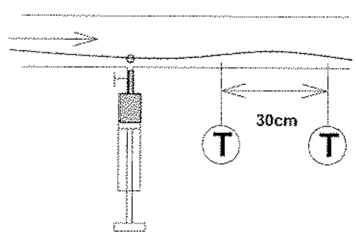
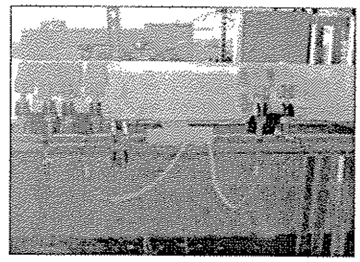
Film Velocity: Cold Liquid Injection

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





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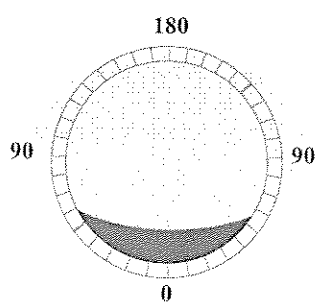
Wet Perimeter: Grades

- Inside Pipe
- Minimize Reading Error



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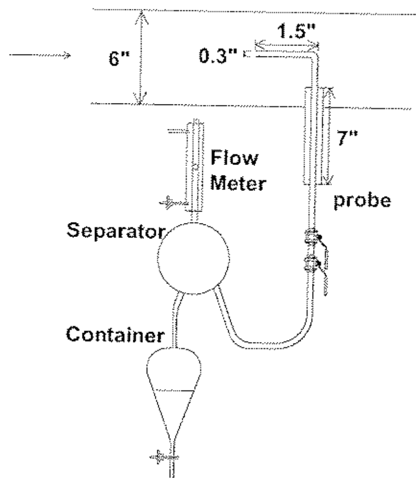
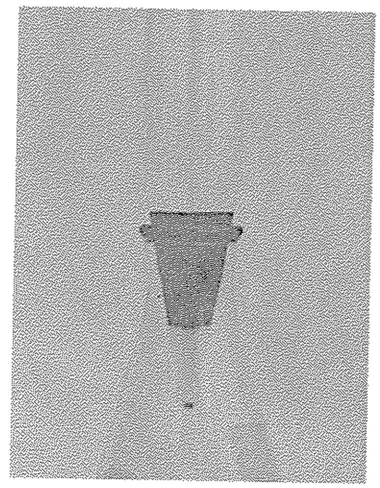
Liquid Entrainment: Iso-kinetic Probe





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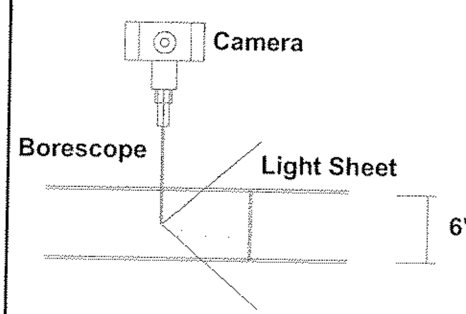
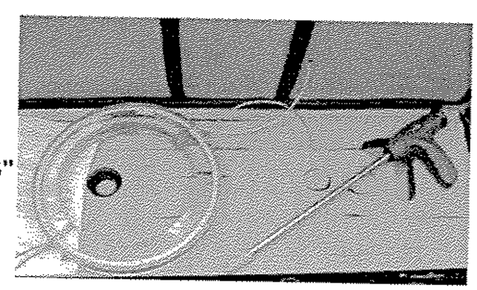
Cross-sectional Viewing System

- Interface Shape





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Test Fluids

- Tap Water/Mineral Oil/Air
- Oil Properties
  - 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, 10, 15 and 17.5 m/s
- Liquid Loading Level:

  50, 300, 600, 900 and 1200 $m^3/MMsm^3$
- Water Cut:

  0, 0.05, 0.1, 0.15, 0.2, 0.5 and 1
- Superficial Liquid Velocity:

  0.00033 to 0.038 m/s

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Experimental Results

- Flow Pattern
- Pressure Gradient
- Holdup
- Wetted Wall Fraction
- Film Thickness
- Liquid Entrainment

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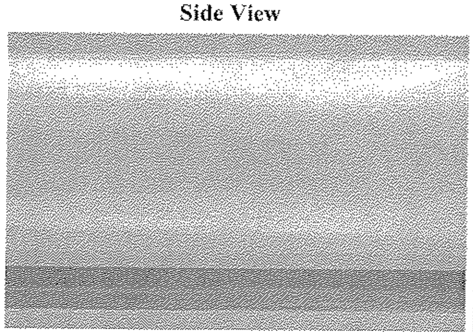
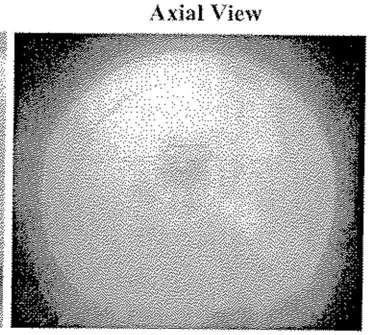
Gas-liquid Flow Pattern

- Stratified Smooth (SS)

Side View



Axial View



$v_{SG} = 5$ m/s, LL = 600 $m^3/MMsm^3$, WC = 0.5

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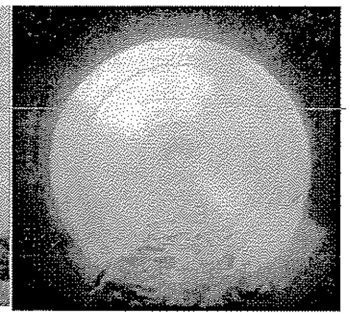
Gas-liquid Flow Pattern ...

- Stratified Wavy (SW)

Side View

Axial View



v_{SG} = 10 m/s, LL = 600 $m^3/MMsm^3$, WC = 0.5

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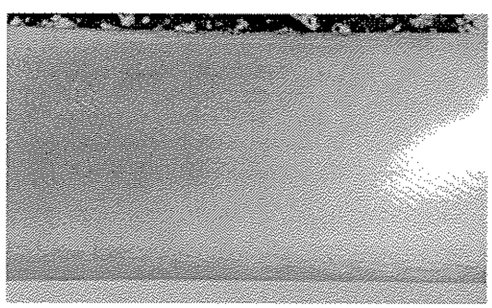
Gas-liquid Flow Pattern ...

- Stratified Wavy and Entrainment (SW & E)

Side View



v_{SG} = 17.5 m/s, LL = 1200 $m^3/MMsm^3$, WC =1

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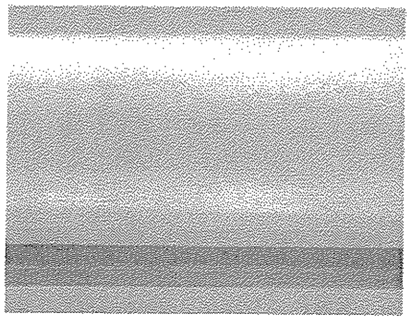
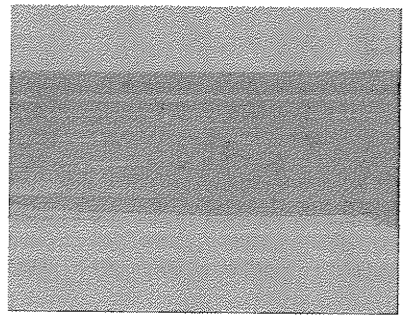
Oil-water Flow Pattern

- Stratified (ST)

Side View



Bottom View



v_{SG} = 5 m/s, LL = 600 m^3/MMsm^3, WC = 0.5

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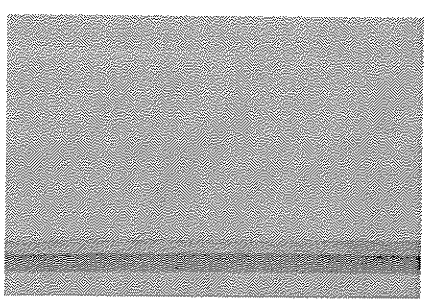
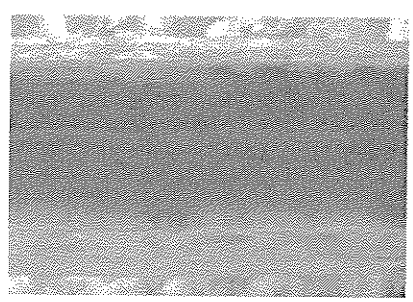
Oil-water Flow Pattern …

- Oil and Discontinuous Water Strip (ODWS)

Side View



Bottom View



v_{SG} = 5 m/s, LL = 600 m^3/MMsm^3, WC = 0.1

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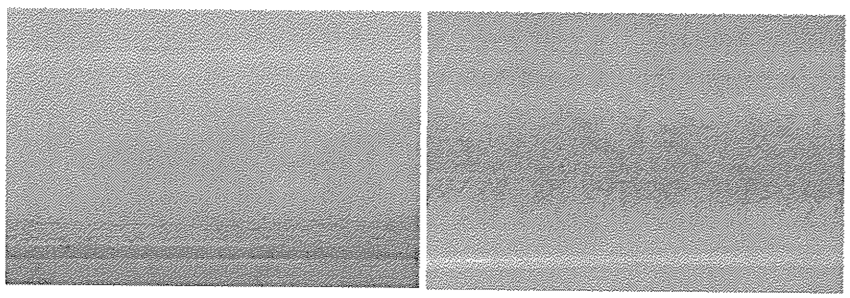
Oil-water Flow Pattern ...

- Water in Oil Dispersion ($D_{W/O}$)

Side View | Bottom View



v_{SG} = 15 m/s, LL = 300 m³/MMsm³, WC = 0.1

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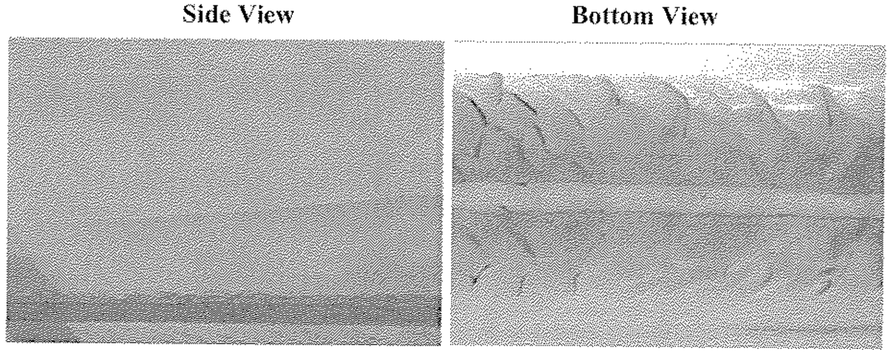
Oil-water Flow Pattern ...

- Stratified with Channel Water and Water in Oil Dispersion (ST_{CW} & $D_{W/O}$)

Side View | Bottom View



v_{SG} = 10 m/s, LL = 300 m³/MMsm³, WC = 0.2

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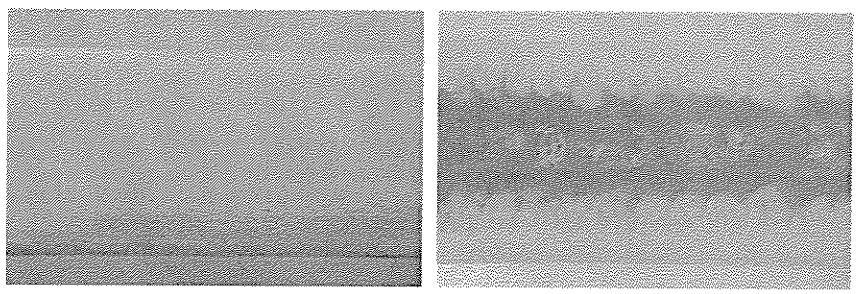
Oil-water Flow Pattern …

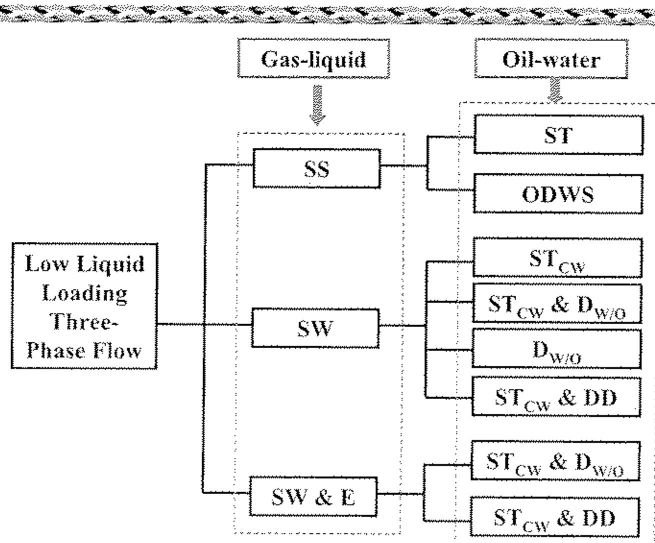
- Stratified with Channel Water and Dual Dispersion (ST_{CW} & DD)

Side View | Bottom View

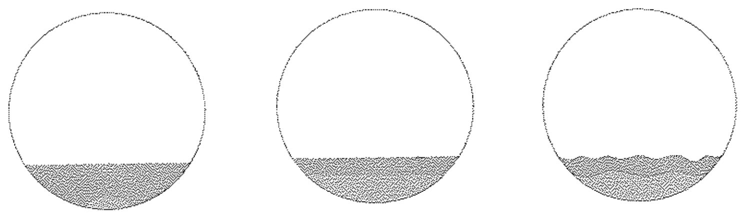


v_{SG} = 17.5 m/s, LL = 900 $m^3/MMsm^3$, WC = 0.5

Three-phase Flow Pattern



Three-phase Flow Pattern ...



(a) SS – ODWS (b) SS – ST (c) SW - ST

Air Oil Water

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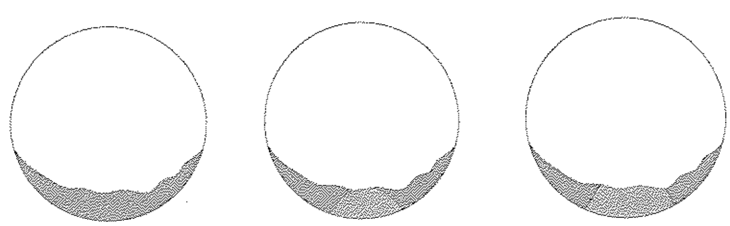
Three-phase Flow Pattern ...



(d) SW – $D_{W/O}$ (e) SW – ST_{CW} & $D_{W/O}$ (f) SW – ST_{CW} & DD

Air Oil Water

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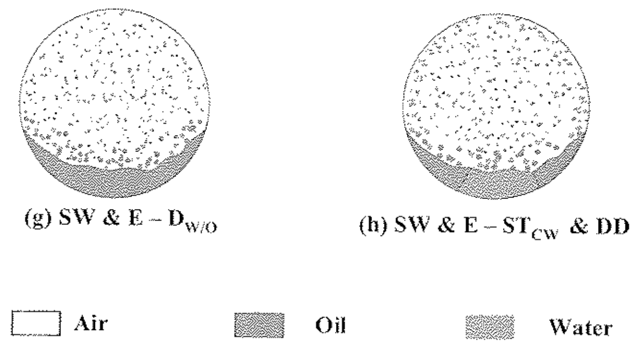
Three-phase Flow Pattern …



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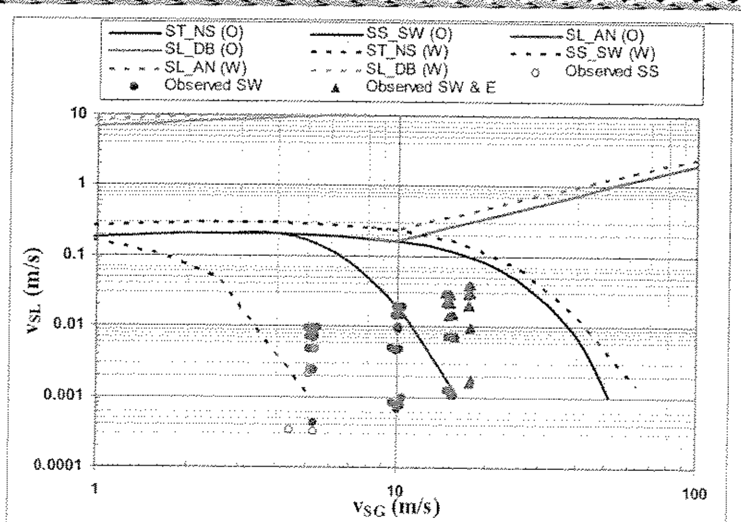
Gas-liquid Flow Pattern Map – Taitel & Dukler (1976)



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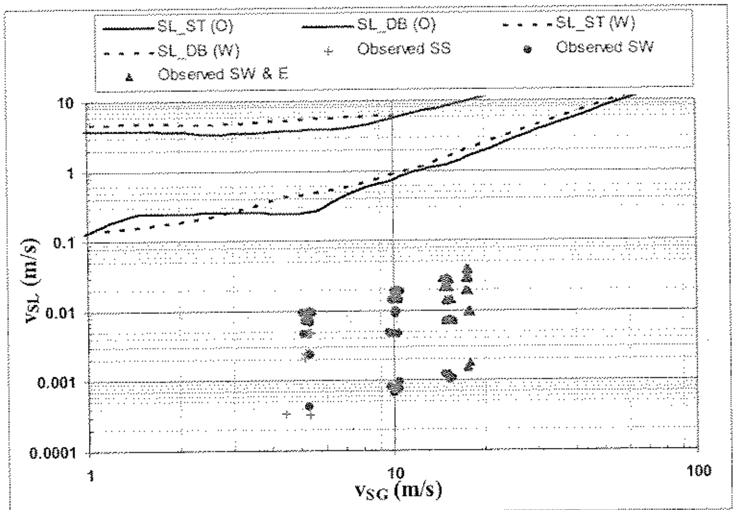
Gas-liquid Flow Pattern Map – Zhang et al. (2003)



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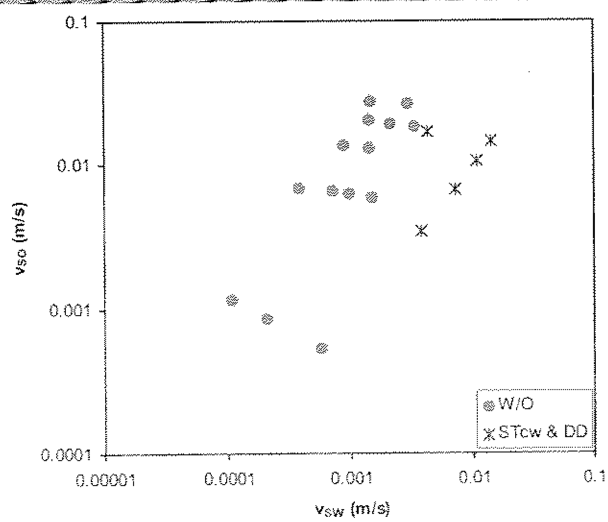
Oil-water Flow Pattern Map (v_{SG} = 15 m/s)



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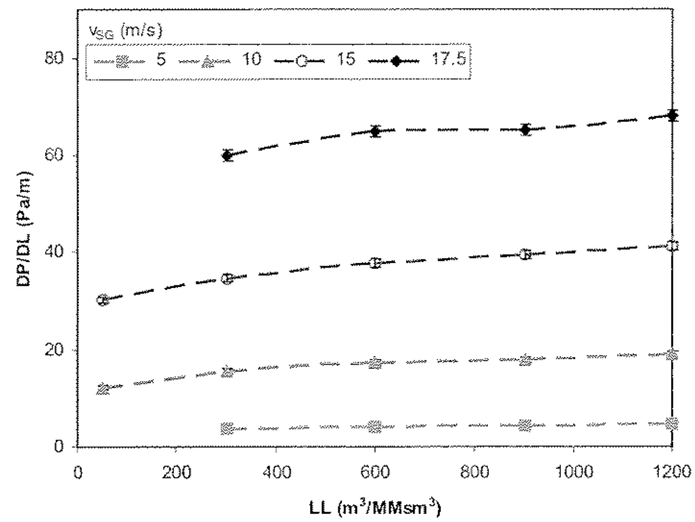
Pressure Gradient (WC = 0.1)



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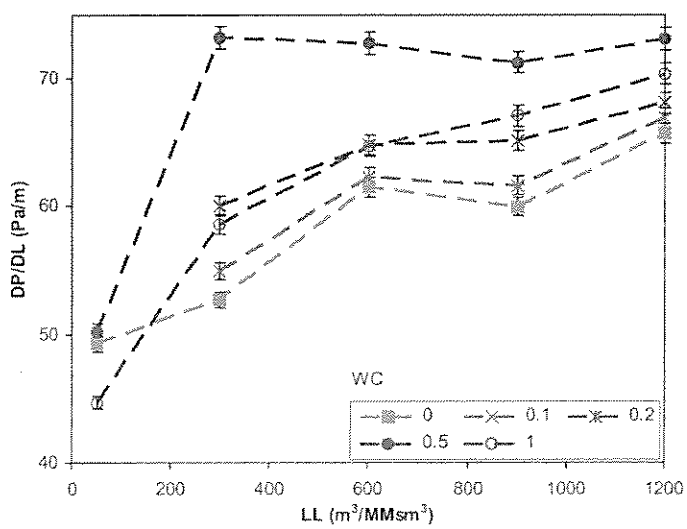
Pressure Gradient (v_{SG} = 17.5 m/s, LL = 1200 m³/MMsm³)



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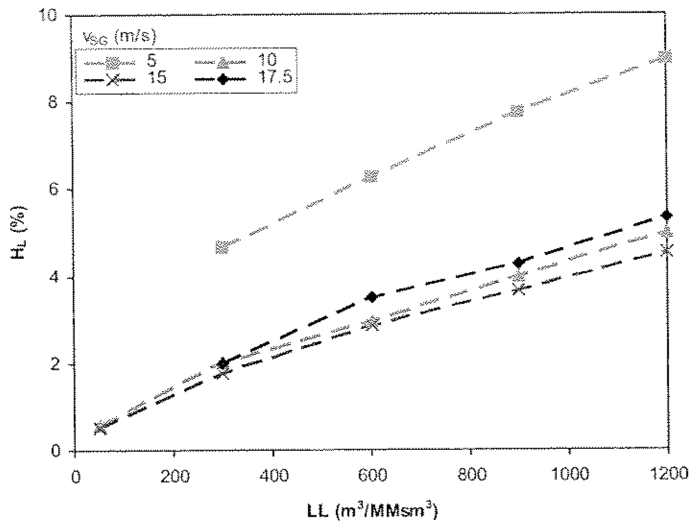
Total Liquid Holdup (WC = 0.2)



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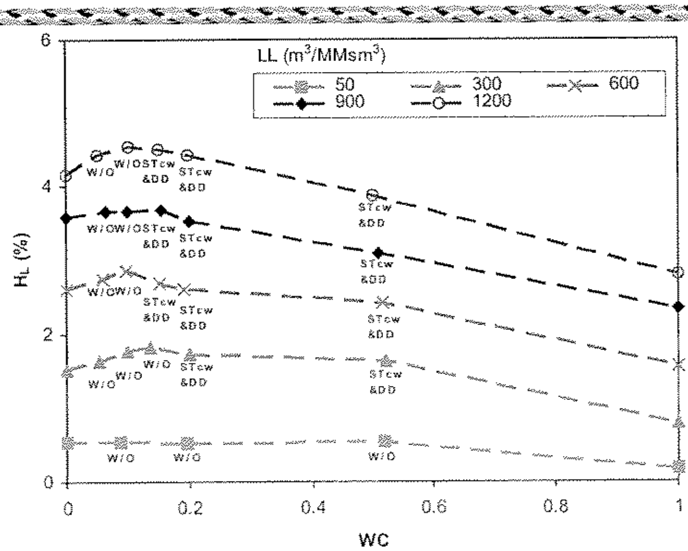
Total Liquid Holdup (v_{SG} = 15 m/s)



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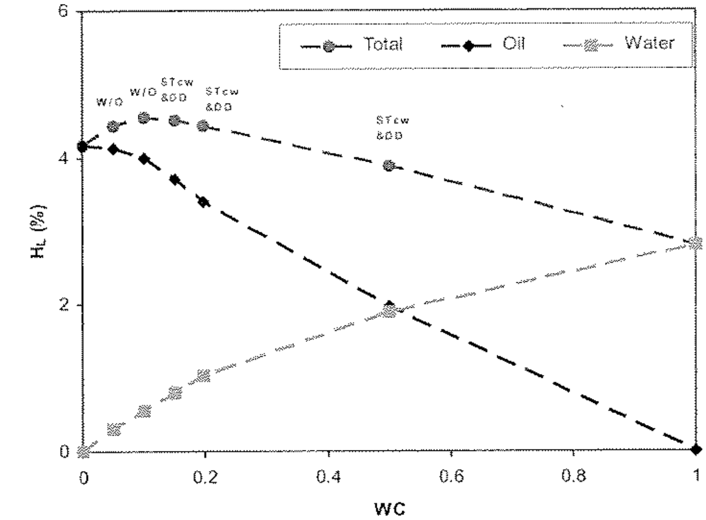
Liquid Holdups (v_{SG} = 15 m/s, LL = 1200)



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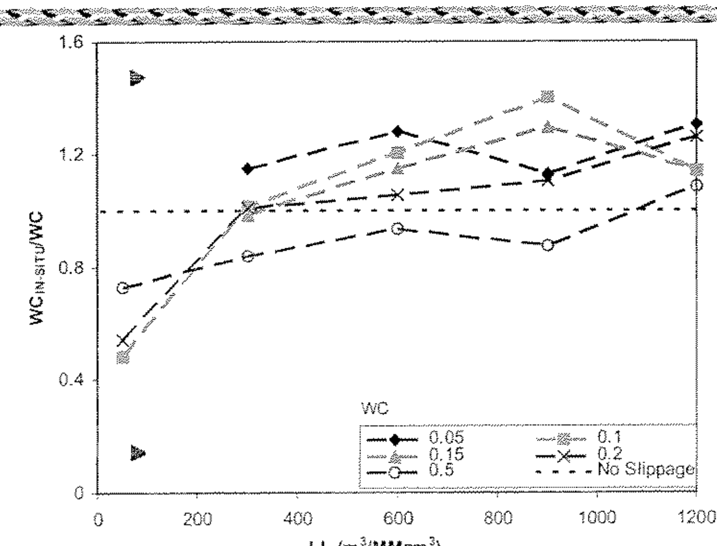
Oil-water Slippage (v_{SG} = 10 m/s)



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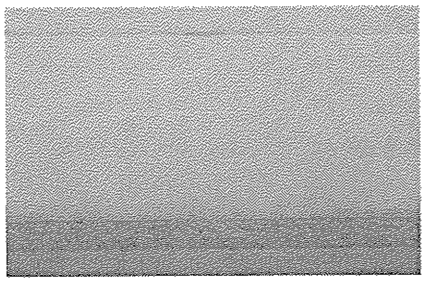
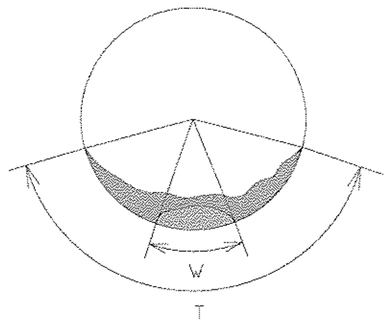
Wetted Wall Fraction





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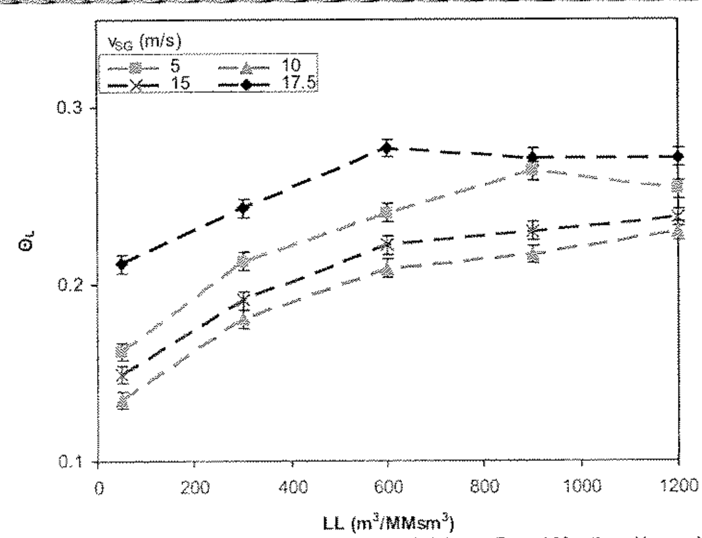
Total Liquid Wetted Wall Fraction (WC = 0)



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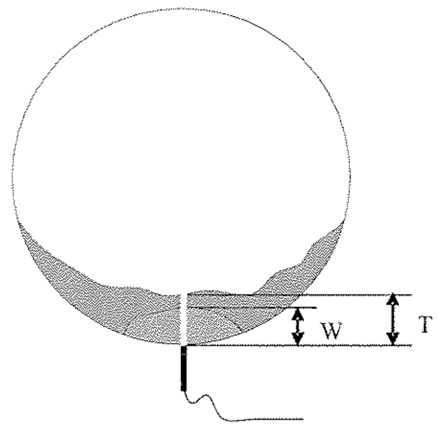
Liquid Film Thickness



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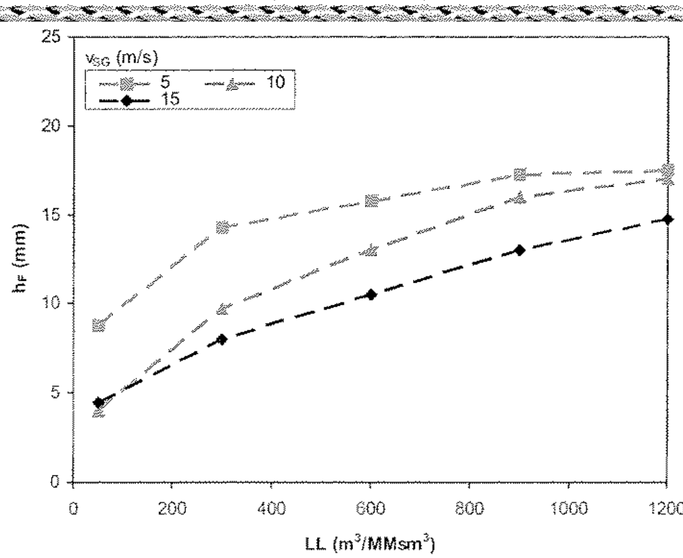
Total Liquid Film Thickness (WC = 0)



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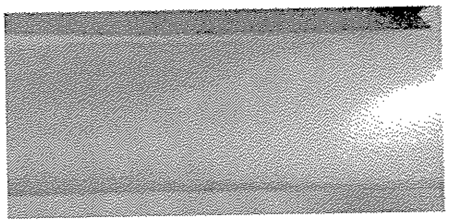
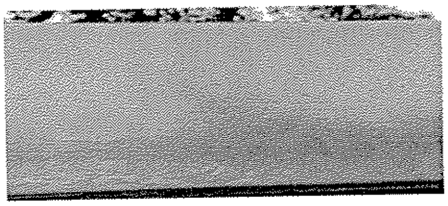
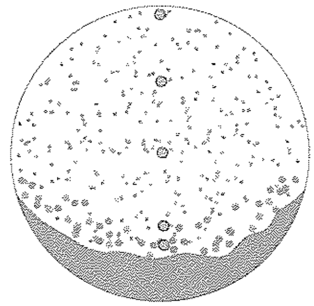
Liquid Entrainment



Liquid Entrainment (WC = 0)



Liquid Entrainment (WC =1)



Measurement Locations

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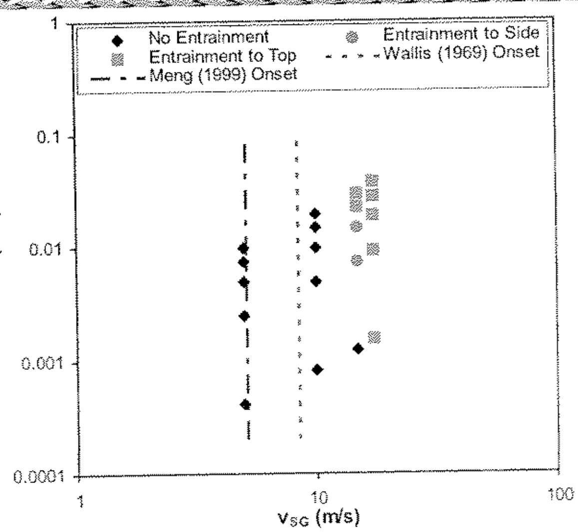
Onset Observation of Entrainment (Oil and Oil-Water)



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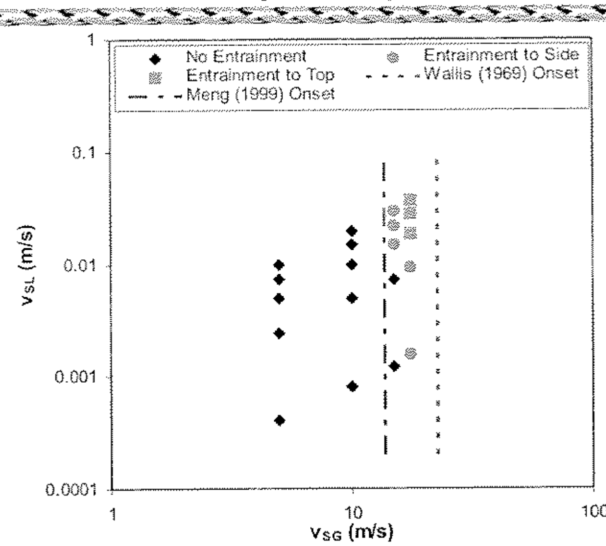
Onset Observation of Entrainment (Water)



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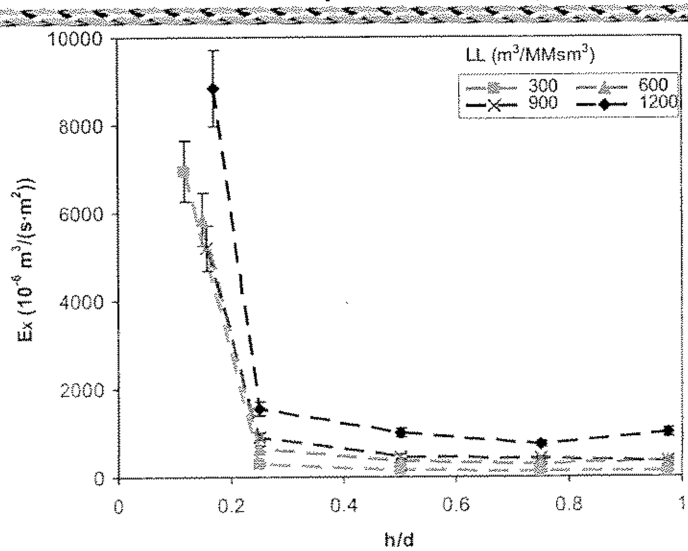
Total Liquid Entrainment Flux Profile (WC = 0.15)



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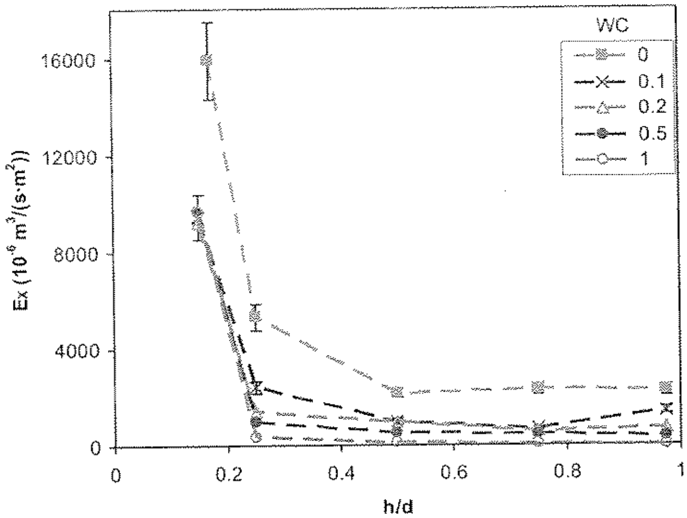
Total Liquid Entrainment Flux Profile (v_{SG} = 17.5 m/s, LL = 1200 m^3/MMsm^3)



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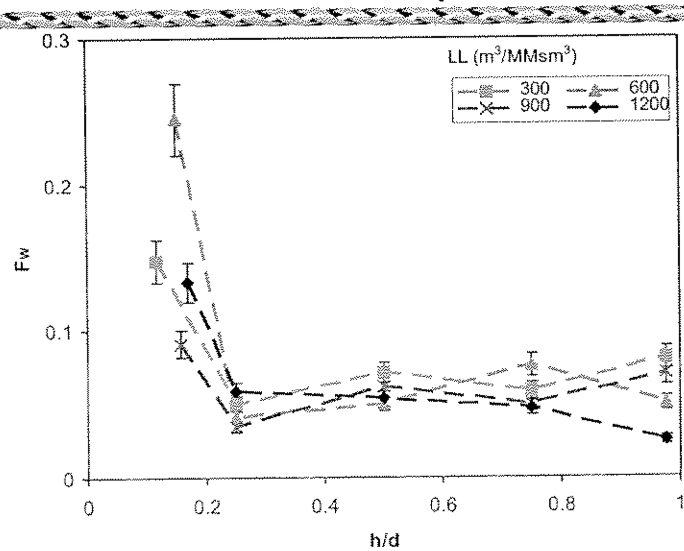
Water Fraction in Liquid Entrainment Profile (WC = 0.15)



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Model Evaluation

- Selected Models

Model	Author
Low Liquid Loading Two-phase Flow Model	Fan (2005)
TUFFP Unified Two-phase Model	Zhang et al. (2003)
TUFFP Unified Three-phase Model	Zhang and Sarica (2006)
OLGA	SPT Group

Model Evaluation – Pressure Gradient

Model	Statistical Parameters					
	ε_1(%)	ε_2(%)	ε_3(%)	ε_4(Pa/m)	ε_5(Pa/m)	ε_6(Pa/m)
Fan (2005)	1.070	8.879	11.235	1.088	3.451	5.752
Zhang et al. (2003)	-8.301	10.967	10.427	-3.638	3.776	4.875
Zhang and Sarica (2006)	-15.848	16.857	27.356	-5.351	5.411	8.691
OLGA	-13.099	13.862	25.356	-3.744	3.984	6.602

Model Evaluation – Total Liquid Holdup

Model	Statistical Parameters					
	$\varepsilon_1(\%)$	$\varepsilon_2(\%)$	$\varepsilon_3(\%)$	$\varepsilon_4(/)$	$\varepsilon_5(/)$	$\varepsilon_6(/)$
Fan (2005)	-7.137	16.854	23.186	-0.004	0.005	0.007
Zhang et al. (2003)	-51.293	54.766	35.385	-0.015	0.015	0.011
Zhang and Sarica (2006)	-59.707	61.929	32.728	-0.017	0.017	0.011
OLGA	-11.706	21.284	26.701	-0.005	0.006	0.007

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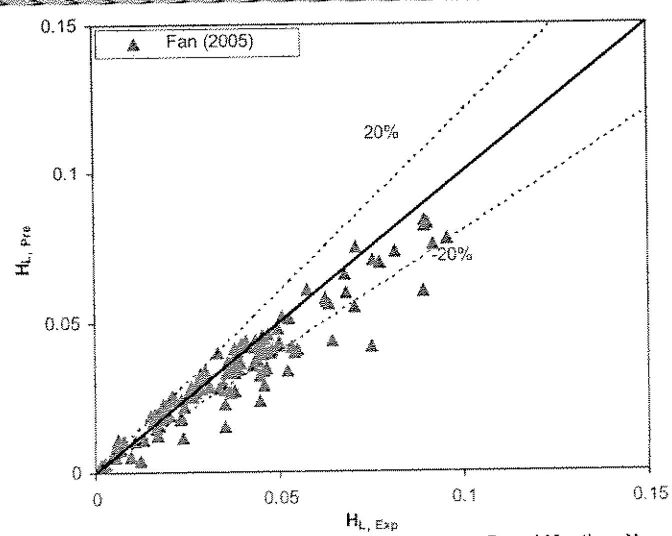
Model Evaluation – Total Liquid Holdup, Fan (2005)



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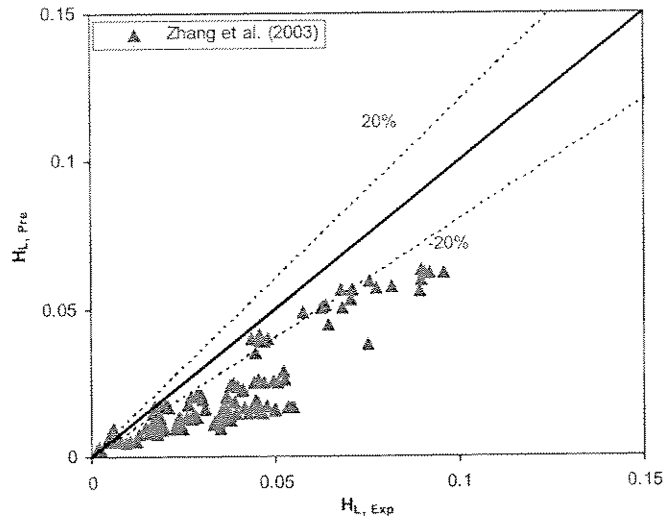
Model Evaluation – Total Liquid Holdup, Zhang et al. (2003)



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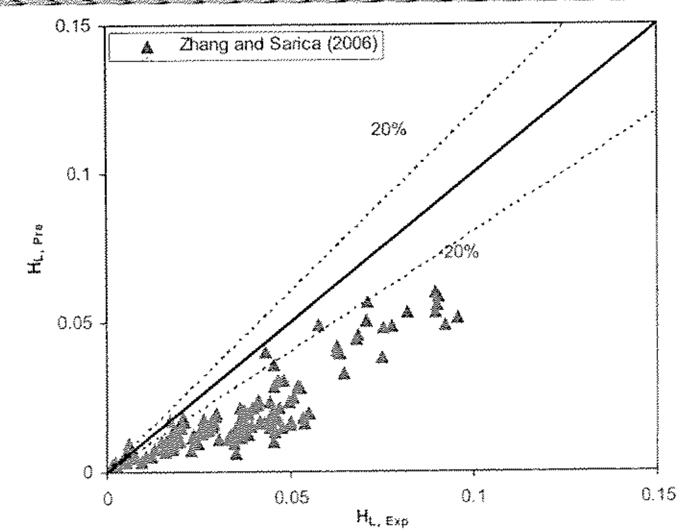
Model Evaluation – Total Liquid Holdup, Zhang and Sarica (2006)



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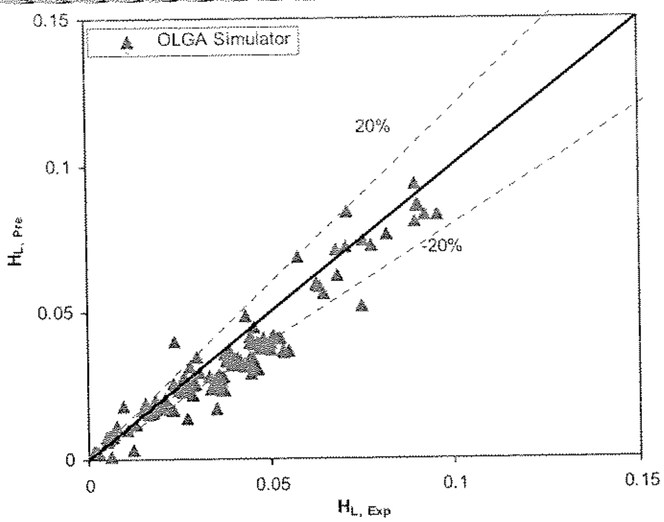
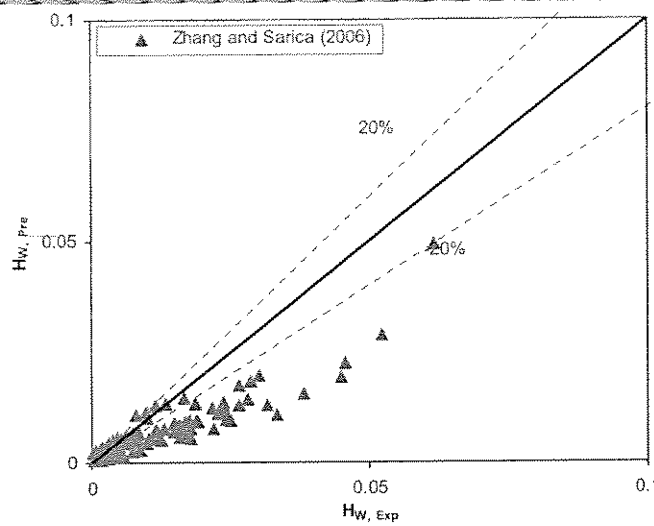
Model Evaluation – Total Liquid Holdup, OLGA



Model Evaluation – Water Holdup

Model	Statistical Parameters					
	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (/)	ε_5 (/)	ε_6 (/)
Zhang and Sarica (2006)	-42.353	56.238	48.921	-0.005	0.006	0.007
OLGA	-10.061	33.777	45.879	-0.003	0.004	0.006

Model Evaluation – Water Holdup, Zhang and Sarica (2006)



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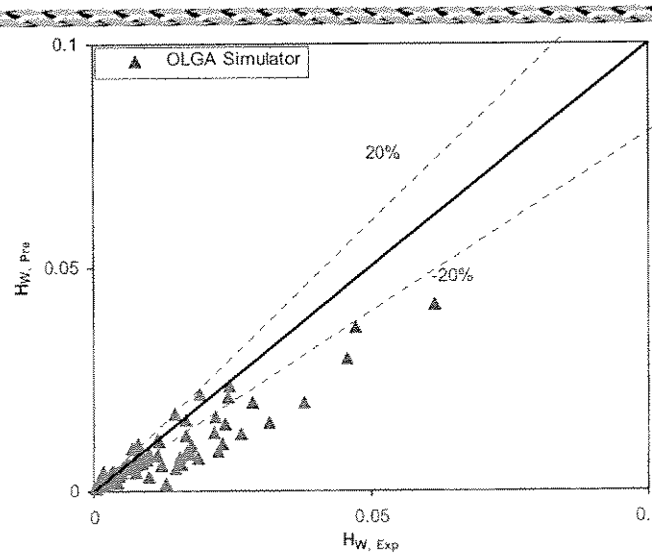
Model Evaluation – Water Holdup, OLGA



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Conclusions

- Low Liquid Loading Gas-oil-water Flow in Large Diameter Pipes is Investigated the First Time
  - 156 Tests Measuring Pressure Gradient, Liquid Holdups, Wetted Wall Fractions, Liquid Film Thickness
  - Oil and Water Entrainment Profiles First Studied

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Conclusions ...

- New Phenomena Observed Including
  - Water Channel Flow
  - Liquid Holdup Rebounds as Gas Velocity Approaches Annular Flow
  - Pressure Gradient first Increases and then Decreases with Increasing Water Cut
  - Liquid Holdup first Increases and then Decreases with Water Cut Increase
  - Wetted Wall Fraction first Decreases and then Increases with Increasing v_{SG}

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Conclusions …

- Model Evaluations
  - Fan (2005) Model Gives Best Predictions of Pressure Gradient and Holdup
  - Zhang and Sarica (2006) Reflects Flow Pattern Changes
  - OLGA Gives Reasonable Predications of Pressure Gradient and Holdup

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Questions and Comments

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

Hongkun (Tom) Dong

PROJECTED COMPLETION DATES:

Literature Review...Completed
Facility Modification ....Completed
Preliminary Testing...Completed
Testing ....Completed
Model Evaluation..Completed
Final Report ....Completed

Objectives

The main objectives of this study are:

- Investigate experimentally and theoretically low liquid loading gas-oil-water flow in horizontal pipes
- Acquire experimental data of low liquid loading gas-oil-water flow in horizontal pipes and identify the differences between low liquid loading two-phase and three-phase flow
- Evaluate existing models with experimental data and suggest modifications or new development for modeling if neccesary

Introduction

Low liquid loading gas-oil-water flow exists widely in wet gas pipelines. These pipelines often contain water and hydrocarbon condensates, while small amounts of condensates can lead to a significant pressure loss along a pipeline (Meng, 2001). Many other issues like hydrate formation, pigging frequency and downstream facilities design are related to the pressure and holdup prediction of pipeline. Moreover, the efficiency of the corrosion inhibitors is strongly related to the distribution of the liquids in the pipeline. Therefore, understanding of the flow characteristics of low liquid loading gas-oil-water flow is of great importance in transportation of wet gas.

Due to the difference in fluid properties, mixture of oil and water may exhibit significant different behaviors from single liquid phase. However, very few studies have been conducted on low liquid loading three-phase flow. No research has been carried out in this specific area with a large diameter pipe up to the author knowledge. Although several studies (Açikgöz et al., 1992; Taitel et al., 1995; Pan, 1996; Khor, 1998; Bonizzi et al., 2003; Oddie et al., 2003, Keskin, 2005; Zhang and Sarica, 2005) have been conducted on three-phase flow pattern and the modeling of three-phase flow, the flow range of low liquid loading flow was not covered in those studies probably due to the complexity and uncertainty.

Low liquid loading gas-oil-water flow experiments were conducted in a 6-in ID flow loop. The pressure drop, holdups, wetted wall fractions, liquid entrainments and liquid film thicknesses with respect to different superficial gas velocities, liquid loadings and water cuts were measured in horizontal pipes.

The experimental data were compared with selected model predictions. Suggestions on model modification were made based on the experimental findings.

Experimental Study

Experimental Facility

The TUFFP 6-in flow loop, which has been used for low liquid loading two-phase flow (Fan, 2005), was modified for three-phase experiments. The schematic of the facility after modifications is shown in Fig. 1.

A vertical three-phase separator was added to the system for separating gas, oil and water phases in the experiments. Inlet momentum is controlled with a bi-directional inlet diverter that also provides bulk gas/liquid separation. A 6-in thick wire mesh extractor is used to de-mist the air. This facilitates the removal of 99% of 5 micron and larger droplets. Oil and water separate in 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 were used as oil and water tanks to supply and circulate liquid for the system. Two cavity pumps were used as oil and water pumps. Two-stage air compressors were used to supply air to the system.

The test section was made of 6-in ID pipes and consists of two runs connected with a U-shape bend. Each run is 56.4-m long. Significant modifications of the test section were made. PVC pipes in the U-shape flow loop have been replaced with steel ones with an acrylic visual section at the end of each run. The schematic of the test section is shown in Fig. 2. A new mixing section shown in Fig. 3 was designed for properly mixing gas, oil and water phase at the entrance of the test section. The inclination angle of the test section can be changed from 0° to 2°, enabling us to have downward flow with inclination angle down to -2° and upward flow with inclination angle up to $+2^{\circ}$ with the two runs, respectively. Both the upward and downward runs of the test section were instrumented.

Instrumentation and Data Acquisition

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

Gas flow rate was measured with a Micro Motion flow meter CMF 300. Two Micro Motion flow meters CMF050 were used to measure oil and water flow rates. They were calibrated by the manufacturer. The uncertainty of mass flow rate was ±0.1% and the uncertainty of density measurement was ±0.5%.

Quick-closing valves were used to trap the liquid to measure the total liquid holdup, water holdup and oil holdup. The liquid entrapped in the quick closing valves was pigged out with a designed pigging system and drained into graduated cylinders to measure the volumes of water and oil phases.

Cold liquid injection method, similar to the salt water injection method (Fan, 2005) which has been used in the low liquid loading of gas-water flow experiments, was applied to measure the interface velocity. A cold liquid injector was placed at a point in the test section to inject cold oil or water into the test section. Two thermal couples were installed 0.5 ft after the injector with a 1 ft interval between them. The time difference between the temperature peaks detected by those two thermal couples is recorded. Then, the liquid velocity was calculated.

Conductivity probe was 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 based on the conductivity change due to phase change. Meanwhile, conductivity probe was also used for the determination of which phase in the fully mixed liquid film is continuous based on the conductivity difference between oil and water during the three-phase experiments.

An iso-kinetic sampling system was used for the determination of liquid entrainment in the gas phase. During the experiments, the iso-kinetic sampling probe traversed in the pipe to obtain the sample at different locations. The liquid in the sample was separated with a small gas-liquid separator and collected in a graduated cylinder. The gas was vented into the atmosphere. The collected liquid volume and the sampling time were used to determine the liquid entrainment. Liquid entrainment at each location was obtained when the probe traversed from bottom to top to get the liquid entrainment profile across the pipe. The principle is shown in Fig. 4.

A cross-sectional viewing system was mounted in the test section to get the image of the cross section. An Olympus rigid borescope, an Olympus SP350 digital camera and a camera-borescope adapter were used for the system. Sheet light illumination was used to illuminate the pipe cross-section. The method was to cover the pipe by dark covers leaving a narrow gap to restrict the light to a narrow area. The principle of axial view system is shown in Fig. 5.

Measuring the wetted wall perimeter from outside the pipe with tape has a significant uncertainty due to the refraction of the pipe wall. The uncertainty changes with the film height and the thickness of the pipe wall. In the present study, the transparent acrylic pipe was marked inside to give a direct reading of the wet perimeter, which significantly reduced the reading uncertainty.

DeltaV™ digital automation system was used as the data acquisition system for low liquid loading three-phase flow. The DeltaV system is a fully digital system, by which it can save time to integrate all the measured parameters and minimize the error.

Test Fluids

The fluids used in the experiments consist of air, mineral oil and tap water. Due to its good separability and stability, Tulco Tech 80 oil is selected as the oil phase. The physical properties of the oil 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 characterization measurements of Tulco Tech 80 mineral oil have been performed in Chevron labs. The changes in density and viscosity with temperature are given in Figs. 6 and 7, respectively.

Testing Range

In this study, superficial gas velocity ranged from 5 to 17.5 m/s. The liquid loading level ranged from 50 to 1200 m^3/MMm^3. Water cut changed from 0 to 100%.

Uncertainty Analysis

The uncertainty analysis was performed for all of the instruments based on the systematic and random uncertainty analysis.

Random errors affect test data in random fashion from one reading to the next (Dieck, 2002). Random uncertainty sources are those that cause scatter in the test results. Generally, when an experiment is conducted, a sample of N population would be used to calculate the standard deviation to get the random error.

$$S_x = \left[\frac{\sum\left(X_i - \overline{X}\right)^2}{N-1}\right]^{1/2}. \qquad (1)$$

where, X_i is the value of i th X in the sample, $\overline{X}$ is the average of sample, $N-1$ is the degrees of freedom for the sample, and S_x is the standard deviation of the sample. Most of time, the standard deviation of the average, $S_{\bar{x}}$, is the preferred format to express the random uncertainty,

$$S_{\bar{x}} = \frac{S_x}{N}. \qquad (2)$$

where $S_{\bar{x}}$ refers to 68% confidence, which means that the interval $\left(\overline{X} \pm S_x\right)$ contains 68% of the data sample.

Generally, 95% confidence is required for most experiments. At this point, Student's t is used as $tS_{\bar{x}}$ to get approximately 95% in confidence. Therefore, the interval $\left(\overline{X} \pm tS_x\right)$ contains 95% of the data sample.

Systematic errors are constant for the duration of experiments. Systematic errors affect every measurement of variables the same amount (Dieck, 2002). It is not observable in the test data. It is the insidious nature of systematic error that, when there is low random error, one assumes the measurement is accurate, with low uncertainty. This is not a sufficient condition for an accurate measurement. The random and systematic errors must both be low to have low uncertainty.

The method in this project for combining systematic uncertainties is to root-sum-square the elemental systematic uncertainties.

$$B/2 = \left[\sum (b_i/2)^2\right]^{1/2}. \qquad (3)$$

Since all these elemental systematic uncertainties are 95% in confidence, the result is also 95% in confidence. The uncertainty analysis for all the parameters measured is listed in the Table 1.

Experimental Procedure

The testing procedure chart is given in Fig. 8. The following six steps of setting up the flow conditions were followed for each test:

Step 1: Set and maintain a gas flow rate.

Step 2: Set and maintain a liquid loading level (total liquid flow rate).

Step 3: Set and maintain a water cut and conduct the experiment to acquire data.

Step 4: Change the water cut and repeat Steps 3 and 4.

Step 5: Change the liquid loading level and repeat Steps 3 to 5.

Step 6: Change the gas flow rate and repeat Steps 2 to 6.

Experimental Results

156 tests were carried out for low liquid loading gas-oil-water flow in horizontal pipes, in which 28 tests are air-water tests under atmospheric pressure and 128 tests were are air-oil-water tests under a system pressure. In the three-phase tests, four superficial gas velocities (5, 10, 15 and 17.5 m/s), five liquid loading levels (50, 300, 600, 900 and 1200 $m^3/MMsm^3$) and seven water cuts (0, 0.05, 0.1, 0.15, 0.2, 0.5 and 1) were used to investigated the three-phase low liquid loading behaviors. The oil flow rate and the water flow rate were determined based on the air mass flow rate, liquid loading level and water cut. The system pressure was maintained between 163 to 185 kPa for the tests.

Flow Pattern

The observed flow patterns of low liquid loading gas-oil-water flow include: stratified-smooth and stratified (SS - ST), stratified-smooth and oil with discontinuous water stripe (SS - ODWS), stratified-wavy and stratified (SW - ST), stratified-wavy and water in oil dispersion (SW - $D_{W/O}$), stratified-wavy and stratified with channel water and water in oil dispersion (SW - ST_{CW} & $D_{W/O}$), stratified-wavy and stratified with channel water and dual dispersion (SW - ST_{CW} & DD), stratified-wavy with droplet entrainment and water in oil dispersion (SW & E - $D_{W/O}$), and stratified-wavy with droplet entrainment and stratified with channel water and dual dispersion (SW & E - ST_{CW} & DD). The classification is shown in Fig. 9, and the schematic of each flow pattern is shown in Figs. 10 (a) to (h).

Pressure Gradient

Selected pressure gradient data are presented in Figs. 11 and 12. As expected, at the same water cut, the pressure gradient increases with increasing the liquid loading at the same superficial gas velocity; it also increases with increasing the superficial gas velocity at same liquid loading level. The water cut does not seem to play an important role on the pressure gradient change for low superficial gas velocity tests except that pressure gradient at water cut of 1 is always lower than that of other cases. At very high gas velocity of 17.5 m/s, the pressure gradient increases to a maximum and then decreases with increasing water cut.

Liquid Holdup

As shown in Figs. 13 and 14, at the same water cuts and the same superficial gas velocities, the total liquid holdup increases with the increasing liquid loading. It is also seen that the total liquid holdups decreases when the superficial gas velocities increases from 5 to 15 m/s at the same liquid loading level and water cut. However, the liquid holdup decreases rapidly when superficial gas velocity increases from 5 to 10 m/s while further increase in superficial gas velocities only causes a very small decrease of total liquid holdup. When the superficial gas velocity increases from 15 to 17.5 m/s, the liquid holdup increases at the same liquid loading and water cut.

The selected water holdup data are presented in Figs. 15 and 16. The water holdup mostly increases with increasing liquid loading at the same superficial gas velocity and water cut. The water holdup also increased as the water cut increased at the same superficial gas velocity and liquid loading. Irregular points were possibly due to the flow pattern transition.

Oil-water slippage is the difference between in-situ oil and water velocities. It is related to water cut ratio ($WC_{in\text{-}situ}/WC$). The selected data for oil-water slippage reflected by water cut ratio are shown in Fig. 17. In low liquid loading gas-water-oil flows, water can flow slower or faster than oil. When the oil and water flow stratified, the gas phase has only contact with oil phase and water layer has to obtain the energy through oil. The upper oil layer flows faster than water layer. At higher gas velocities and higher water cuts, where the stratified with channel water (ST_{CW}) exists, the water layer have a direct contact with gas phase. Since both oil and water could directly acquire energy from gas phase, the viscosity effect came into play, making the oil flow slower than water due to the higher viscosity of oil phase. On the other hand, at very high gas velocity, high turbulent energy made the oil and water flow as fully dispersion or emulsion, the water cut ratio approached 1.

Wetted Wall Fraction

As shown in Fig. 18, the total liquid wetted wall fraction increases as the liquid loading increases at the same gas velocity and water cut. The total liquid wetted wall fraction reaches a minimum value at about v_{SG} of 10 m/s for the same water cut and liquid loading under the investigated flow conditions.

The water wetted wall fraction is shown in Figs. 19 and 20. It is zero many times because the water phase was not continuous. Once the water phase is continuous, the increase of liquid loading results in an increase of water wetted wall fraction at the same water cut and superficial gas velocity.

Film Thickness

The selected total liquid film thickness data are presented in Figs. 21 and 22. At the same water cut and the same superficial gas velocities, the film thickness increases with the increase of liquid loadings because of the increase of input liquid flow rate. The film thickness decreases with increasing superficial gas velocities at the same water cut and liquid loading.

Liquid Entrainment

The onset of liquid entrainment was observed visually. The results are shown in Figs 23 and 24. For oil or oil-water mixture as the liquid phase, the liquid entrainments were first observed at the superficial gas velocity of 15 m/s and liquid loading of 300 m^3/MMsm^3. The entrained droplets first reached the top of the pipe at the superficial gas velocity of 15 m/s and liquid loading of 900 m^3/MMsm^3. For the water as the liquid phase, the liquid entrainment was firstly observed at the superficial gas velocity of 15 m/s and liquid loading of 900 m^3/MMsm^3, and first reached at the top of the pipe at the superficial gas velocity of 17.5 m/s and liquid loading of 900 m^3/MMsm^3.

In the present study, local liquid entrainment flux is defined as the following equation.

$$E_X = \frac{V_E}{A_{probe} t_s} \cdot \qquad (4)$$

Where, E_X is the liquid entrainment flux; V_E : is the collected liquid entrainment volume, A_{probe} is the area of probe opening, and t_s is the sampling duration

The selected total liquid entrainment flux profiles are shown in Figs. 25 and 26. At superficial gas velocities of 17.5 m/s, the same liquid loading and water cut, the entrainment flux on the gas-liquid interface was considerably higher than other locations. The liquid entrainment flux decreases first sharply and then slowly to a plateau from the liquid surface to higher locations. At the same location and same water cuts, the liquid entrainment increased as the liquid loading increased. The total liquid entrainment flux decreased as the water cut increased at each location within the investigated flow conditions.

As shown in Fig. 27, the water fraction in the total entrained liquid is close to the input water cut near the gas-liquid interface. It also decreases to a plateau from the interface to the higher locations.

Model Evaluation

The experimental data were compared with the predictions of the Fan (2005) low liquid loading two-phase flow model, Zhang et al. (2003) unified two-phase flow model, Zhang and Sarica (2006) unified three-phase flow model and the OLGA steady state simulator.

Statistical Parameters

Statistical parameters are used to examine the performance of existing models and software. These statistical parameters are calculated from two types of errors, relative error e_1 and actual error e_2 , which are expressed as in Eqs. 5 and 6, respectively.

$$(e_1)_i = \left[\left(\frac{A_{PRE} - A_{EXP}}{(A_{PRE} + A_{EXP})/2}\right)\times 100\right]_i , \qquad (5)$$

and

$$(e_2)_i = (A_{PRE} - A_{EXP})_i \cdot \qquad (6)$$

In Eqs. (5) and (6), A_{EXP} is the experimental measurement and A_{PRE} is the predicted value by a model. In Eq. (5), instead of using the experimental measurement, the average of the experimental and predicted values is used as the denominator, which is believed to give a more fair representation of the prediction quality (Fan, 2005). Based on the above two types of errors, the following six statistical parameters can be defined.

Average relative error is

$$\varepsilon_1 = \frac{1}{N}\sum_{i=1}^{N}(e_1)_i \cdot \qquad (7)$$

Absolute average relative error is

$$\varepsilon_2 = \frac{1}{N}\sum_{i=1}^{N}|(e_1)|_i \cdot \qquad (8)$$

Standard deviation about average relative error is

$$\varepsilon_3 = \sqrt{\frac{\sum_{i=1}^{N}((e_1)_i - \varepsilon_1)^2}{N-1}}\,. \quad (9)$$

Average actual error is

$$\varepsilon_4 = \frac{1}{N}\sum_{i=1}^{N}(e_2)_i\,. \quad (10)$$

Absolute average actual error is

$$\varepsilon_5 = \frac{1}{N}\sum_{i=1}^{N}|(e_2)|_i\,. \quad (11)$$

Standard deviation about average actual error is

$$\varepsilon_6 = \sqrt{\frac{\sum_{i=1}^{N}((e_2)_i - \varepsilon_4)^2}{N-1}}\,. \quad (12)$$

In the above equations, N is the total number of data points.

Pressure Gradient

The evaluation results of pressure gradient were shown in Table 2. The Fan (2005) low liquid loading two-phase flow model has the smallest values for five of the six statistical parameters, giving the best prediction of pressure gradient. The positive ε_1 and ε_4 values indicate slight overestimation of the pressure gradient. The Zhang et al. (2003) unified two-phase model, the Zhang and Sarica (2006) model and the OLGA simulator all have negative ε_1 and ε_4 values, indicating underestimation of pressure gradient to different degrees.

Figures 28 to 31 show the comparisons of measured pressure gradients and the predicted values with the models. The Fan (2005) model gives very good predictions for low pressure gradient, which corresponds to low superficial gas velocities of 5 and 10 m/s. The predictions become more scattered at high superficial gas velocities of 15 and 17.5 m/s, where the interface curvature and entrainment were encountered. Probably this is because liquid mixture properties and the liquid entrainment effect were not properly taken into account.

The Zhang et al. (2003) model gives slight under predictions compared to most of the data. Since the model is also two-phase flow model the liquid mixture properties may not be reflected by the interpolation. The Zhang and Sarica (2006) three-phase model also under predicts the pressure gradients compared with the experimental data while significant offsets are found on some points, which are marked with the dashed ellipses.

The OLGA model gives good predictions when the superficial gas velocity is less than 10 m/s. It underestimates the pressure gradient at superficial gas velocities of 15 and 17.5 m/s.

Liquid Holdup

Table 3 shows the results of the evaluation of total liquid holdups using the present study data. All the models give negative values of ε_1 and ε_4, indicating that they all underestimate the total liquid holdup compared with the experimental data under the investigated flow conditions. The Fan (2005) low liquid loading two-phase flow model has the smallest values of all the statistical parameters, performing the best in predicting the total liquid holdup. Second to the Fan (2005) model, the OLGA simulator also gives good predictions for the total liquid holdup. The Zhang et al. (2003) model and Zhang and Sarica (2006) model both significantly under predict the total liquid holdup.

Figures 32 to 35 show the comparisons of the individual model predictions with the measured total liquid holdup values. It can be seen that the oil-water flow pattern transition effect is not reflected by the two-phase models. The Zhang and Sarica (2006) three-phase model clearly shows the right trend of the total liquid holdup change with the water cut, but the predictions are all significantly lower than the experimental measurements. The OLGA software appears to be sensitive to the oil-water flow pattern changes, but with a wrong trend.

Water Holdup

The two-phase flow models can not give predictions of oil or water holdup individually. Only the Zhang and Sarica (2006) unified three-phase model and OLGA predictions are compared with experimental data. Table 4 shows the model evaluation results for water holdup with the experimental data of the present study. Both of them underestimate the water holdup (negative ε_1 and ε_4 values). OLGA predictions are better than that of the Zhang and Sarica (2006) model predictions. Figures 5-11 and 5-12 show the individual comparison results of model predictions with experimental measurements.

Conclusion

In this study, 156 tests were carried out for low liquid loading gas-oil-water flow in a 152.4-mm ID horizontal pipe. This is the first experimental study on low liquid loading there-phase flow in large diameter pipes. Pressure gradient, liquid holdups, wetted wall fractions and liquid film thickness were measured in the experiments. Oil and water entrainment profile was also investigated.

Several new flow phenomena were observed in the experiments. A new oil-water flow pattern of water channel flow was observed. This flow pattern perhaps exists only in large diameter pipe. The liquid holdup first decreases and then increases with increasing gas velocity as gas-liquid flow pattern approaches annular flow. The pressure gradient and liquid holdup all first increase and then decrease with increasing water cut. The liquid wetted wall fraction first decreases and then increases with increasing superficial gas velocity.

Several selected two-phase and three-phase mechanistic models are evaluated with experimental results. The Fan model gives the best predictions of pressure gradient and liquid holdup. The Zhang and Sarica (2006) model reflects the flow pattern changes. The OLGA simulator gives reasonable predictions of pressure gradient and liquid holdup.

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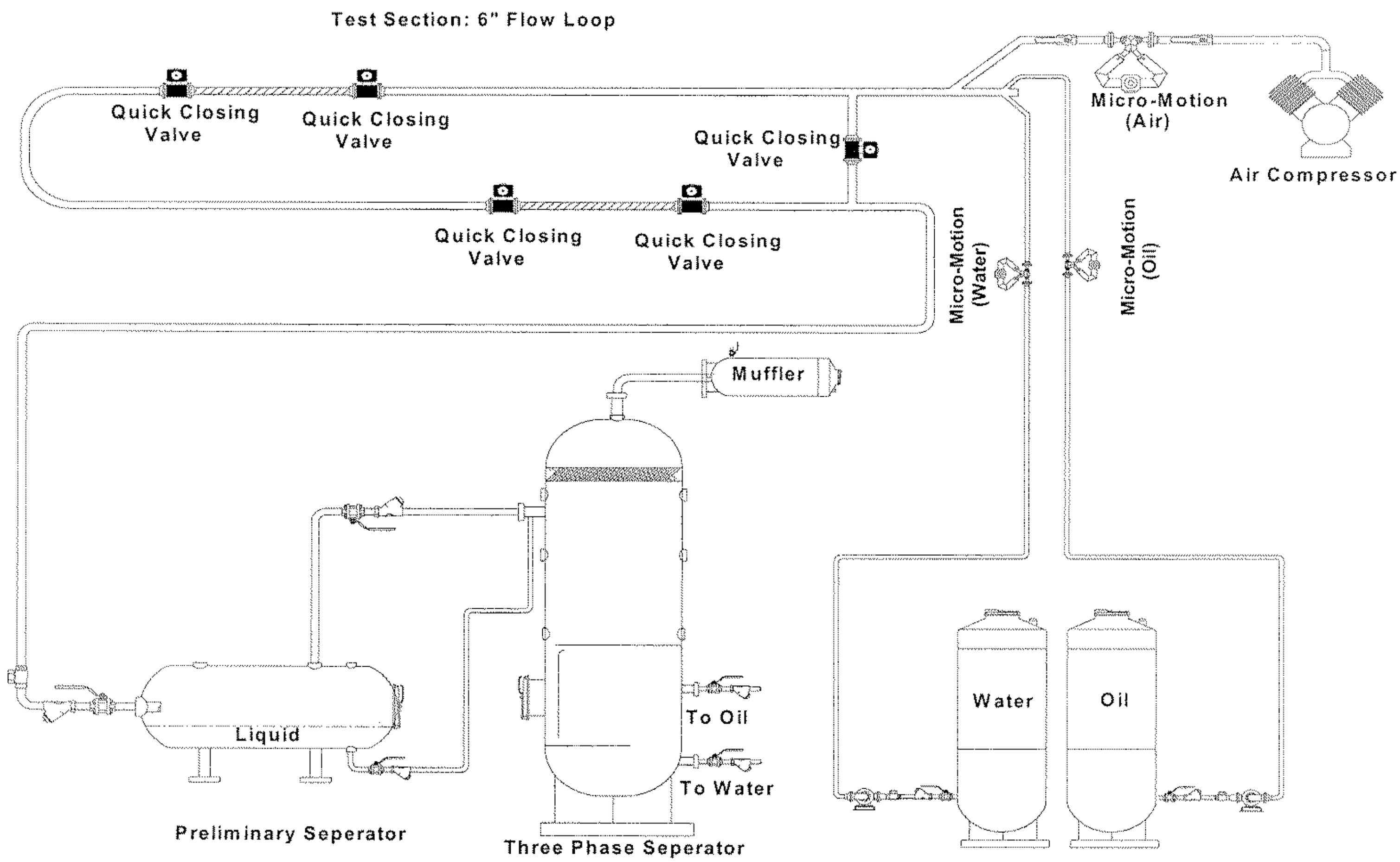

Figure 1: Schematic of Flow Loop

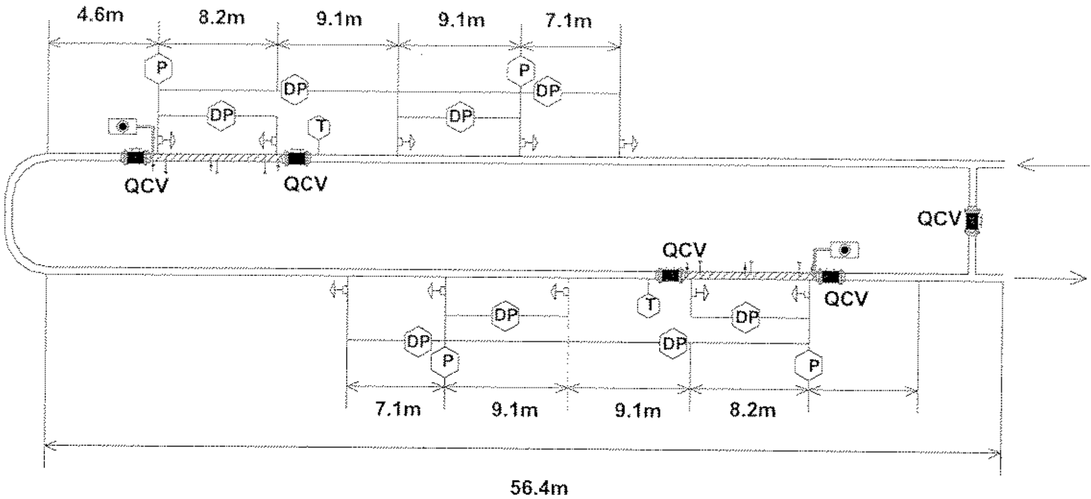

Figure 2: Schematic of Test Section

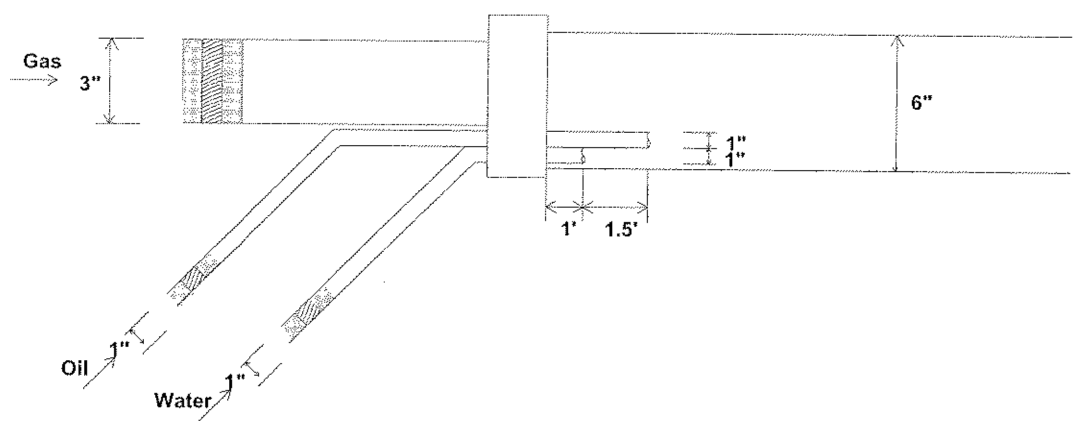

Figure 3: Schematic of Mixing Section

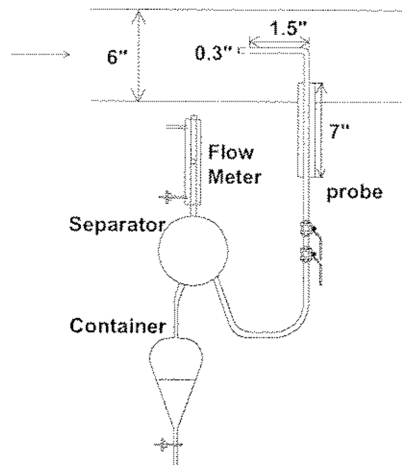

Figure 4: Schematic of Iso-kinetic Sampling System

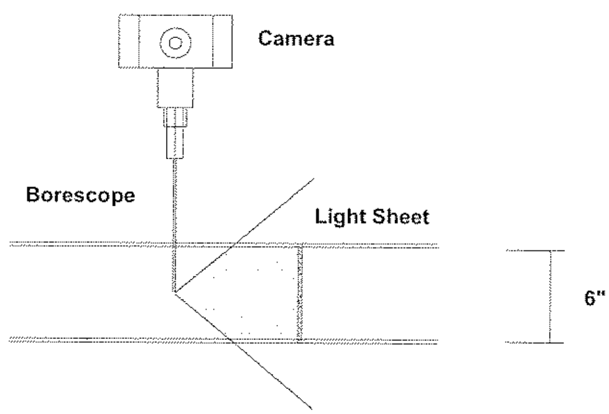

Figure 5: Schematic of Cross-sectional Viewing System

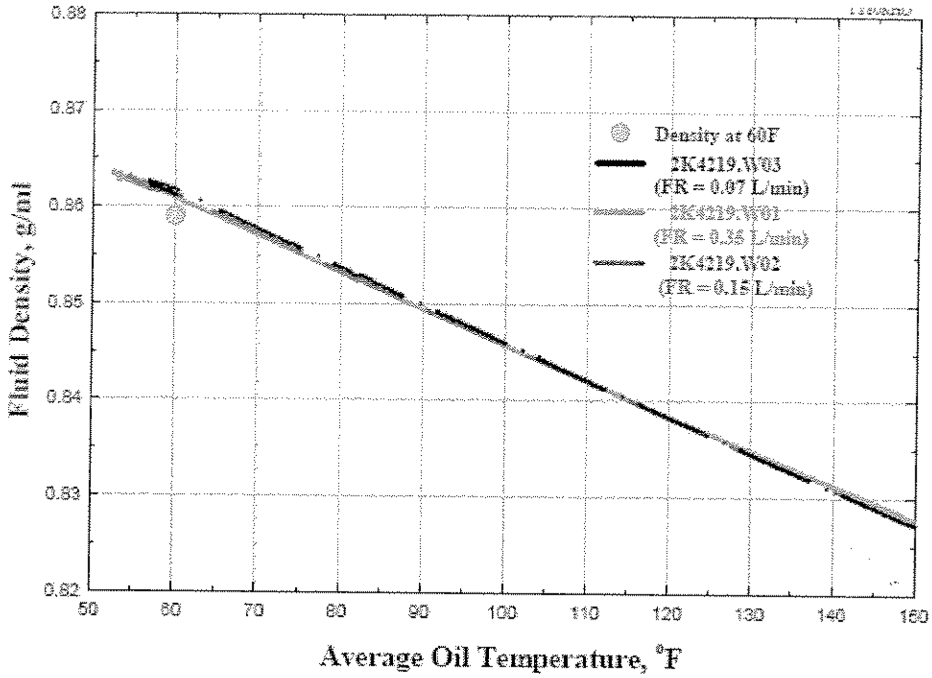

Figure 6: Tulco Tech 80 Oil Density

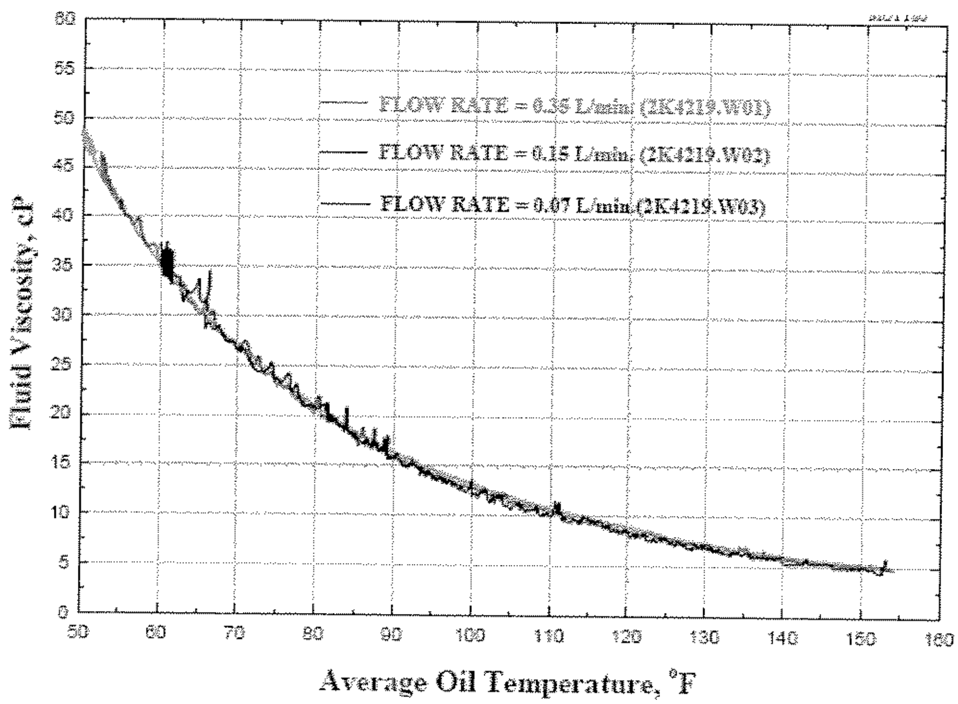

Figure 7: Tulco Tech 80 Oil Viscosity

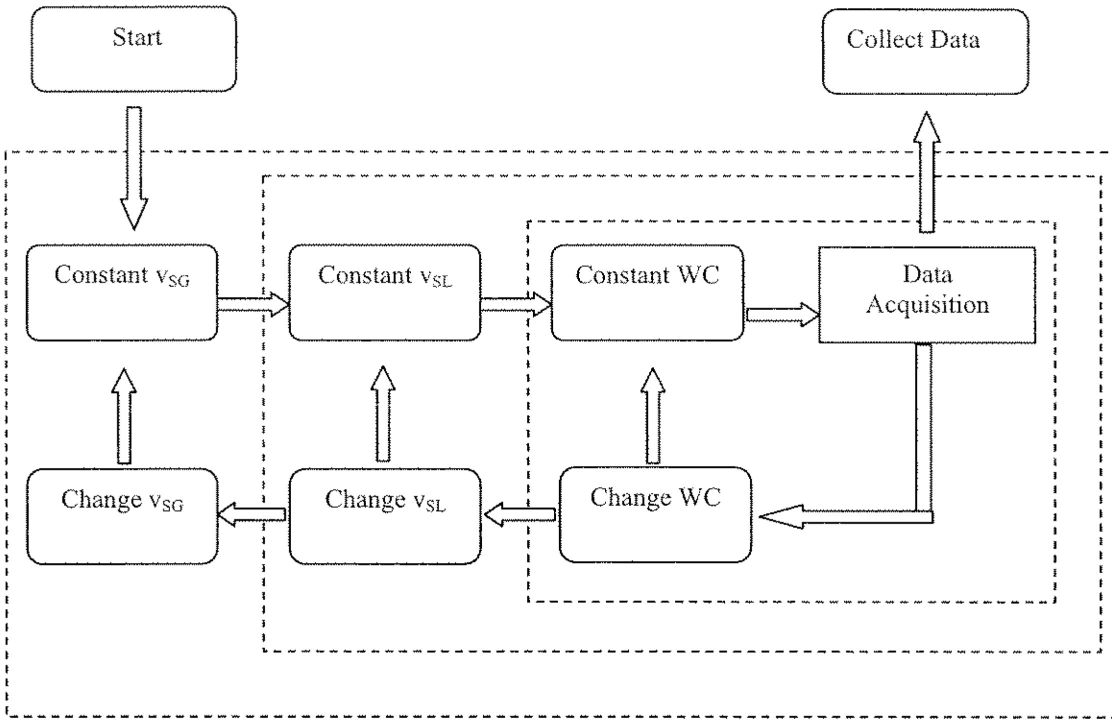

Figure 8: Flow Chart of Experimental Procedure

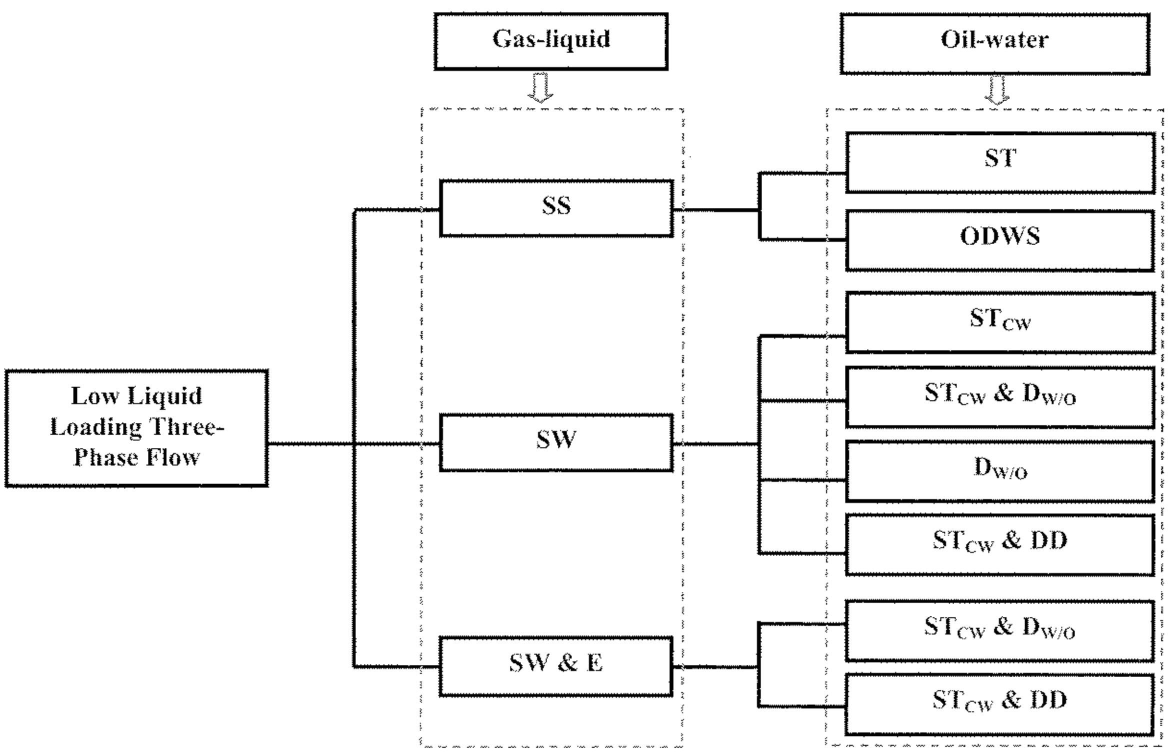

Figure 9: Observed Low Liquid Loading Horizontal Three-phase Flow Patterns

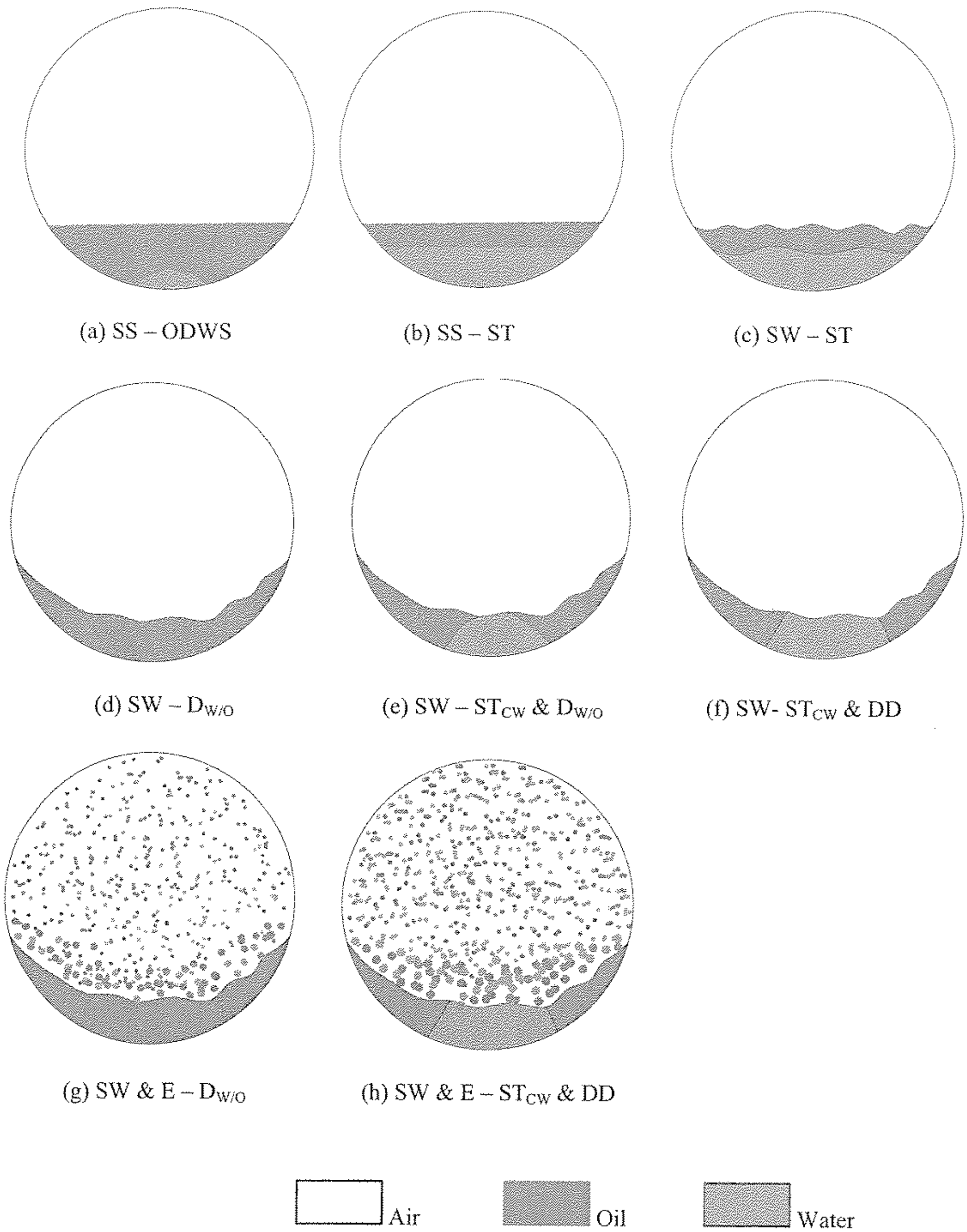

Figure 10: Schematic of Observed Low Liquid Loading Three-phase Flow Pattern Patterns

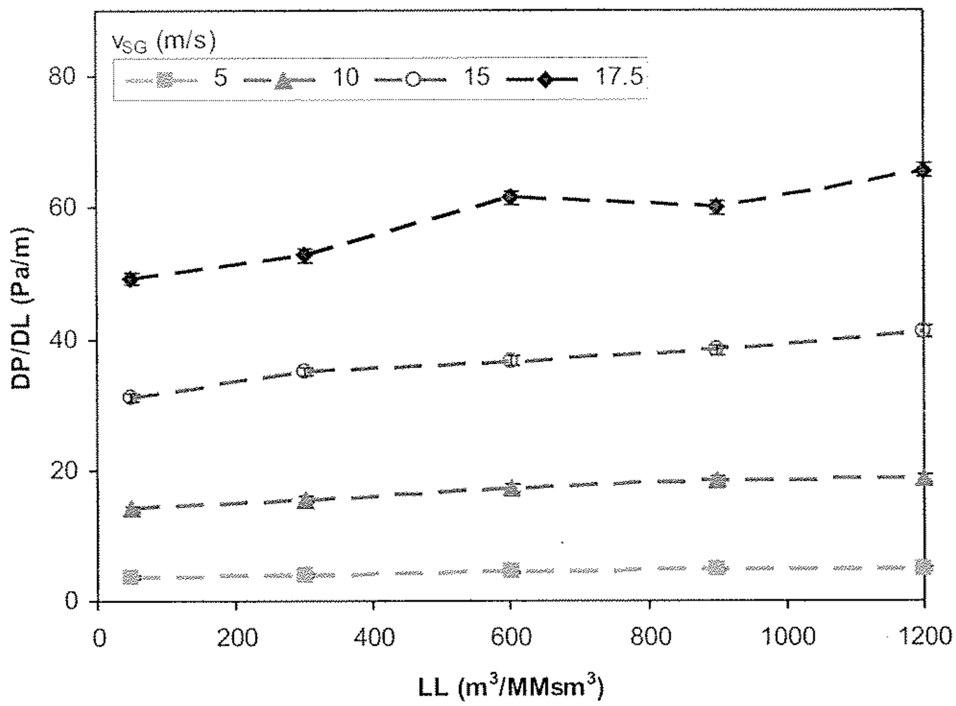

Figure 11: Pressure Gradient (WC = 0)

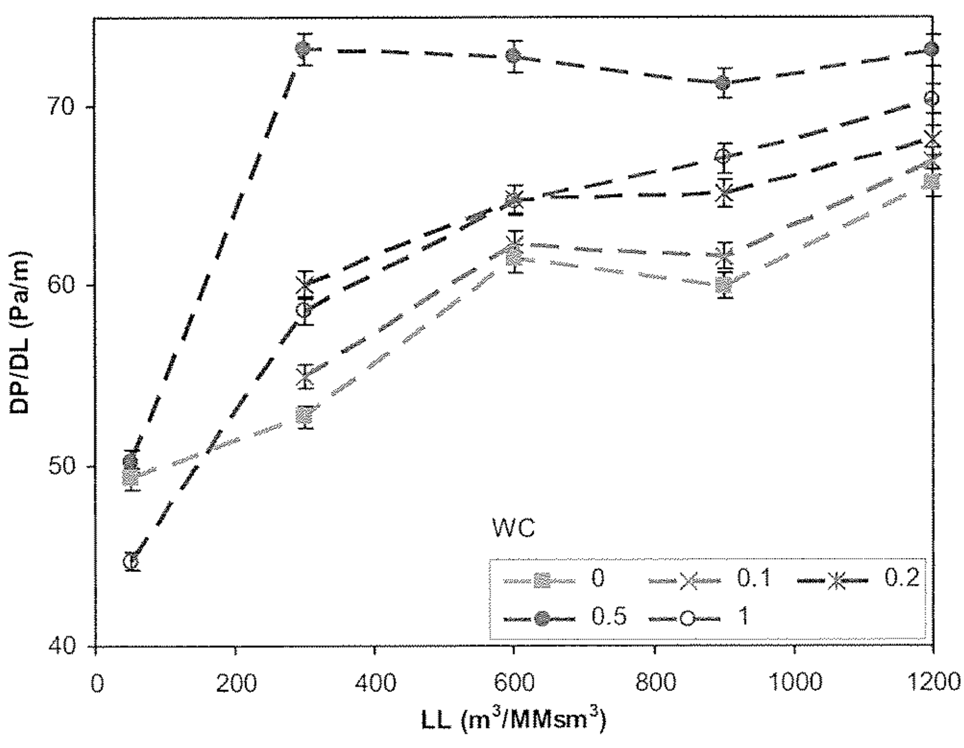

Figure 12: Pressure Gradient (v_{SG} = 17.5 m/s)

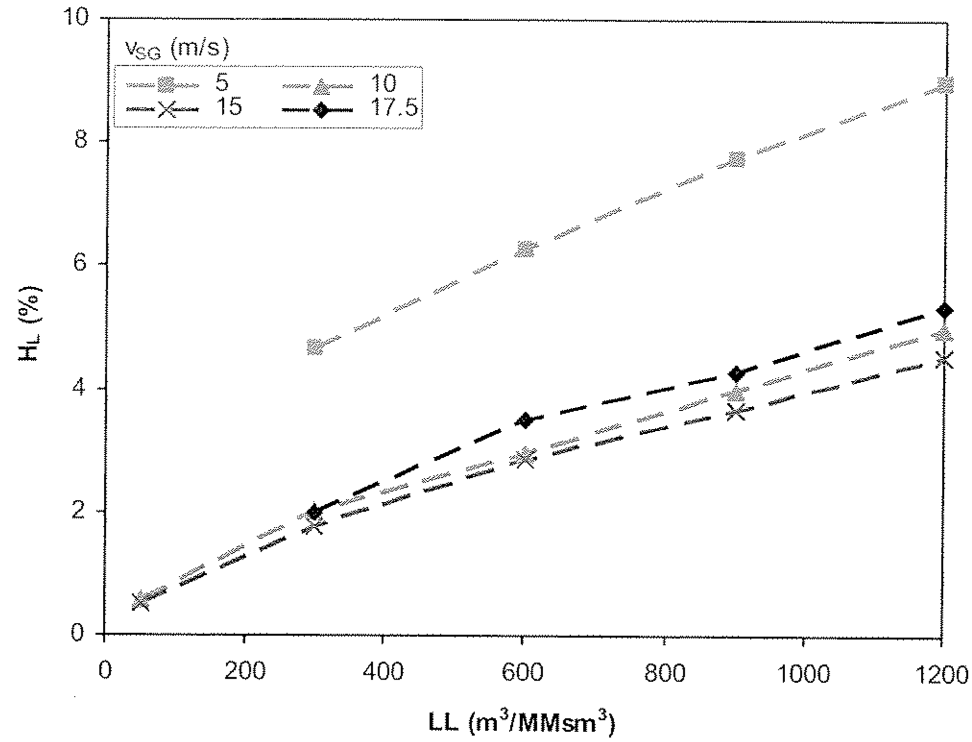

Figure 13: Total Liquid Holdup (WC = 0.1)

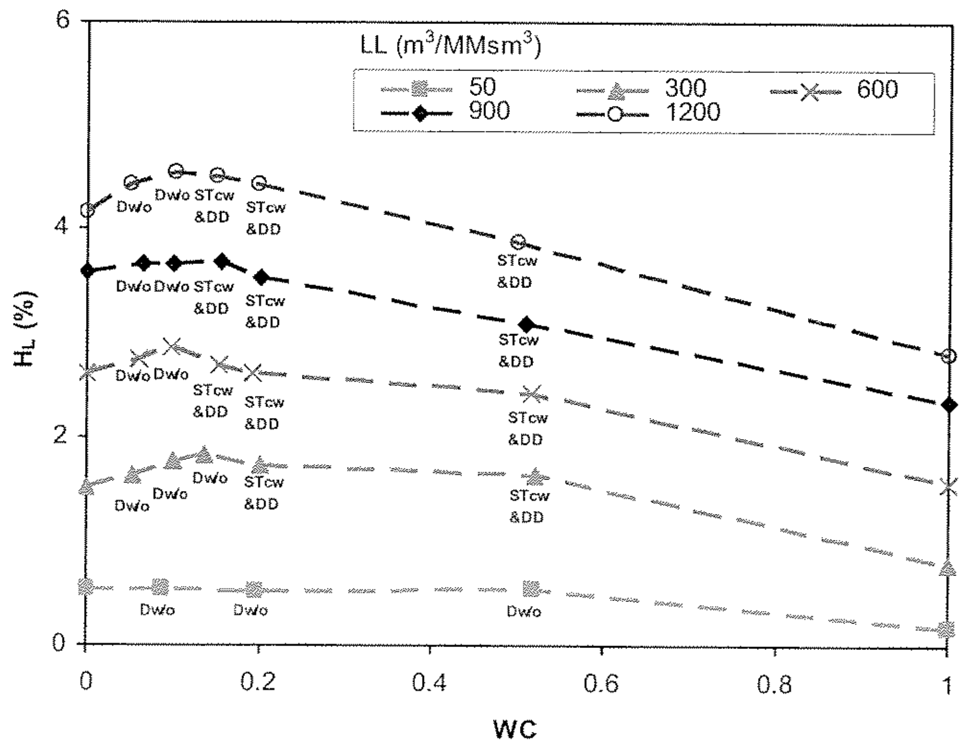

Figure 14: Total Liquid Holdup (v_{SG} = 15 m/s)

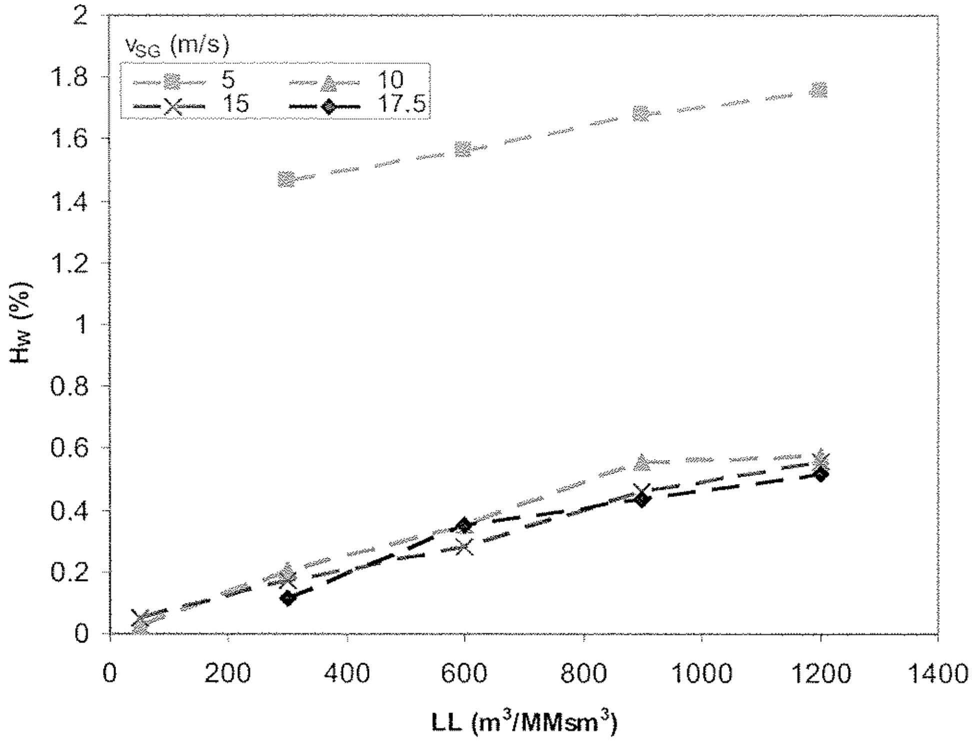

Figure 15: Water Holdup (WC = 0.1)

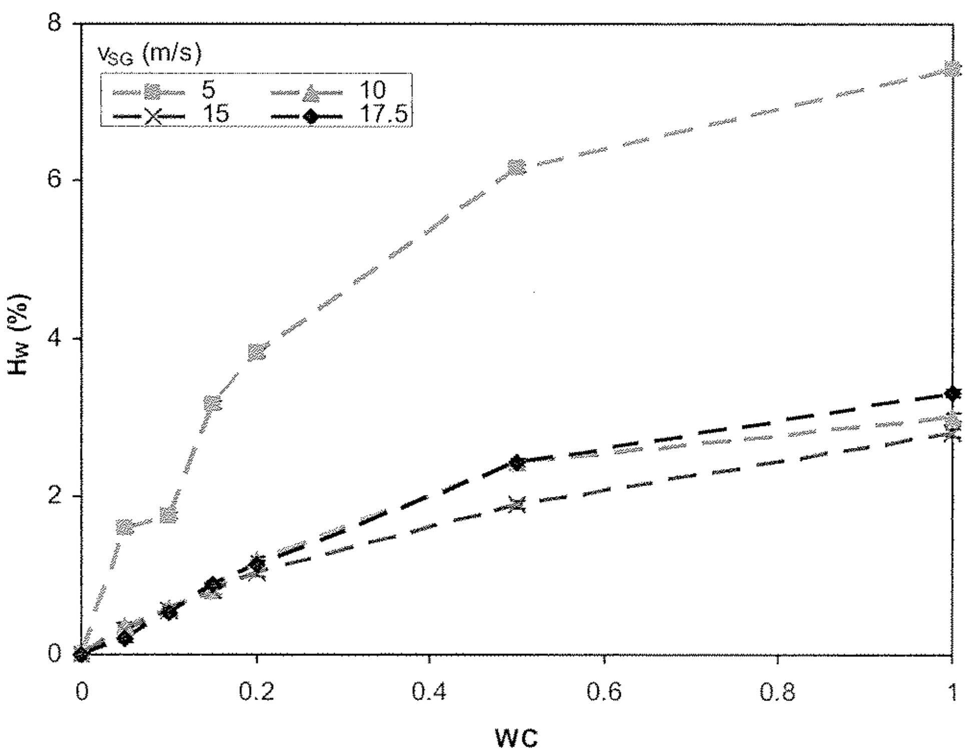

Figure 16: Water Holdup (LL = 600 m^3/MMsm^3)

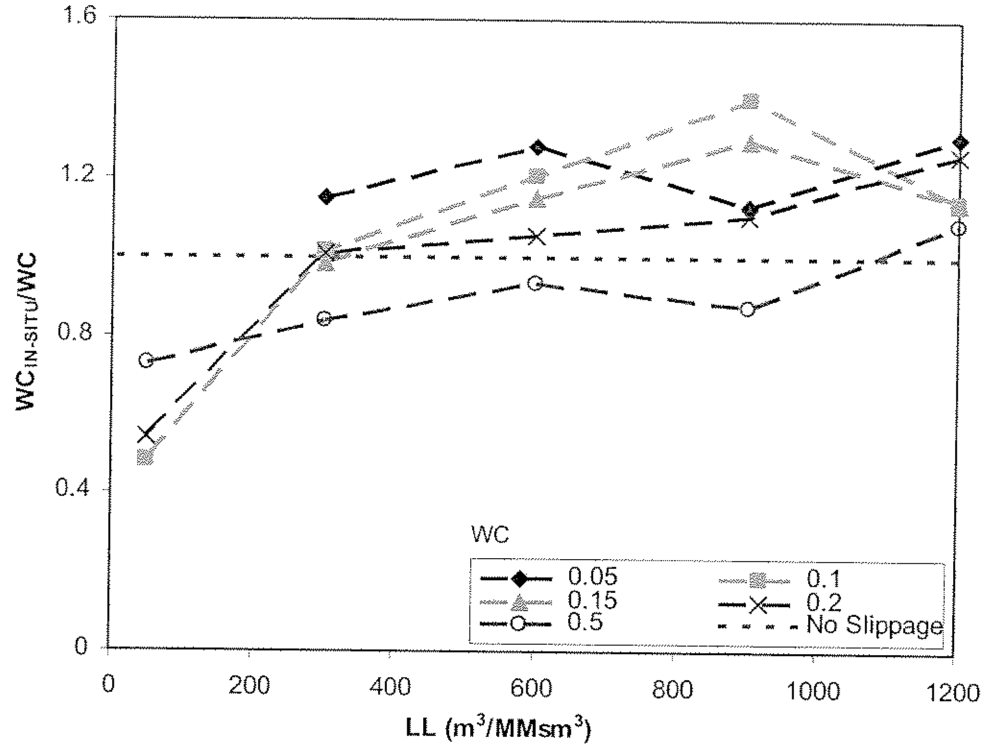

Figure 17: Oil-water Slippage Reflected by Water Cut Ratio (v_{SG} = 10 m/s)

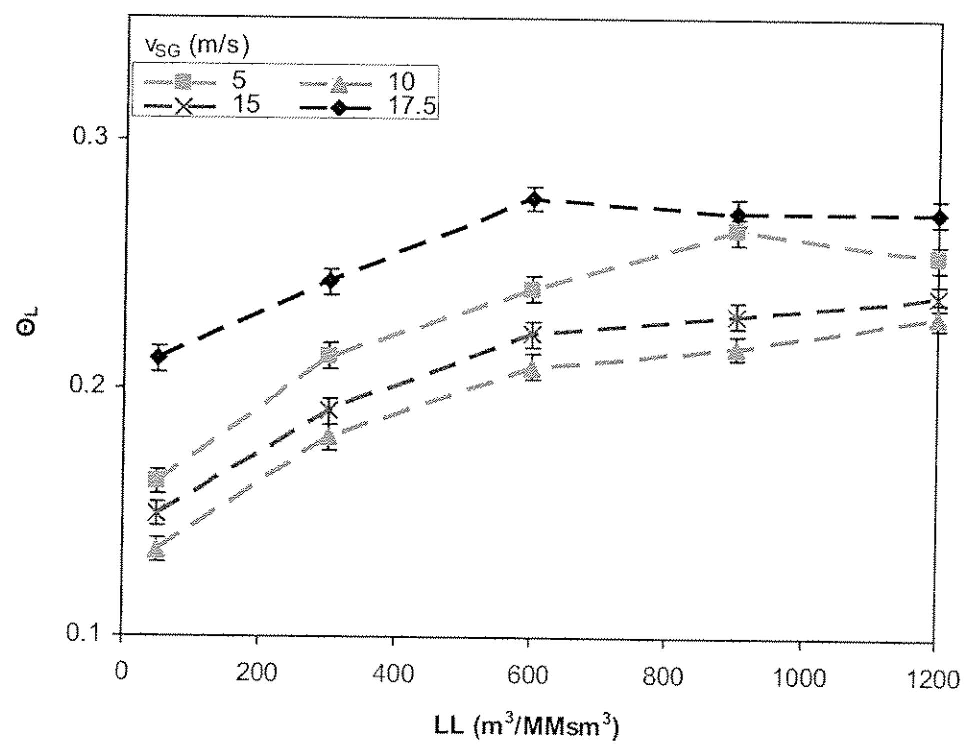

Figure 18: Total Liquid Wetted Wall Fraction (WC = 0)

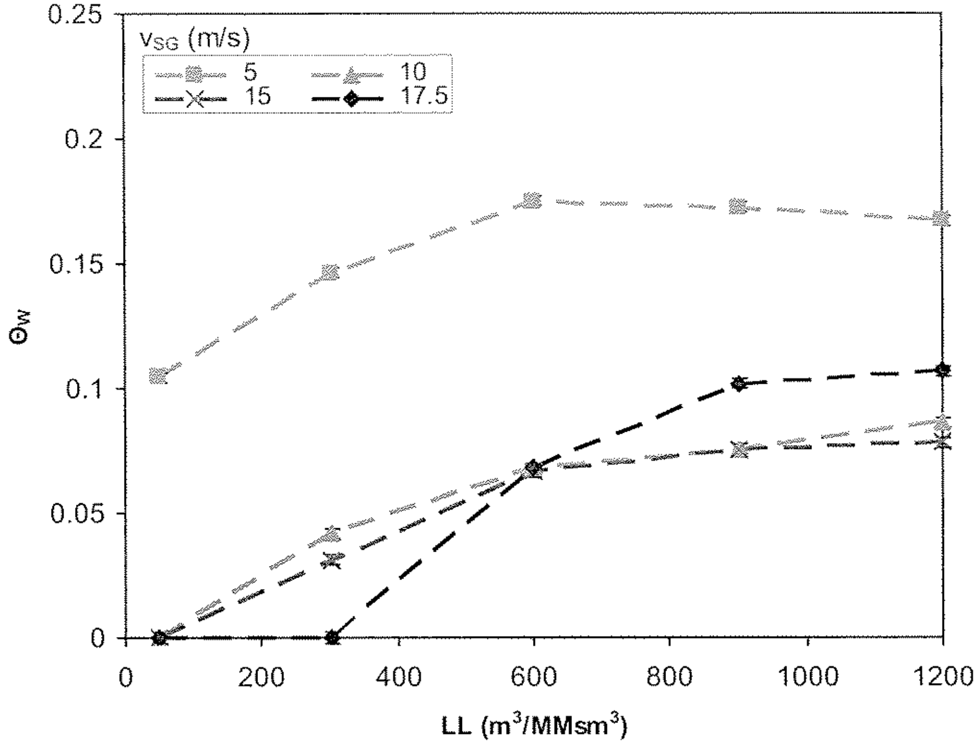

Figure 19: Water Wetted Wall Fraction (WC = 0.5)

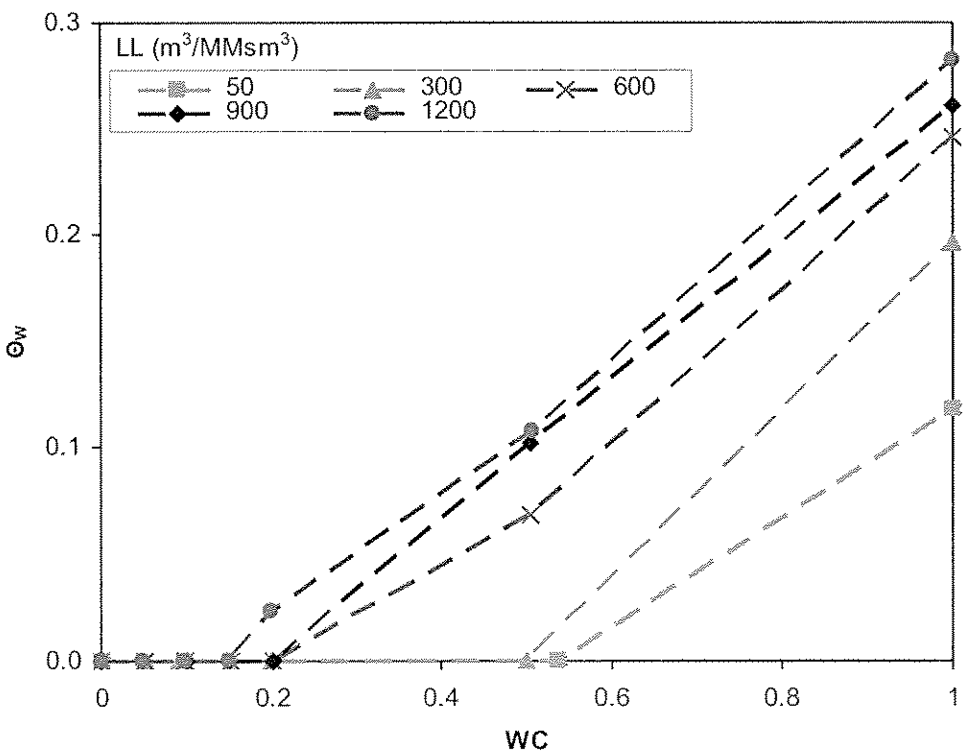

Figure 20: Water Wetted Wall Fraction (v_{SG} = 10 m/s)

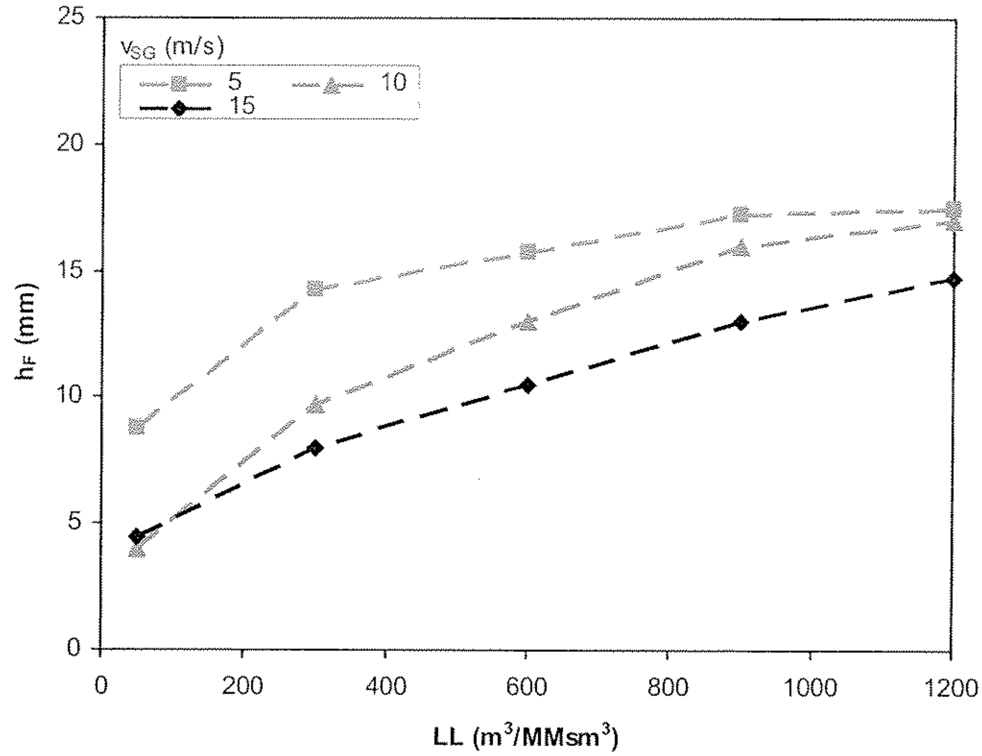

Figure 21: Total Liquid Film Thickness (WC = 0)

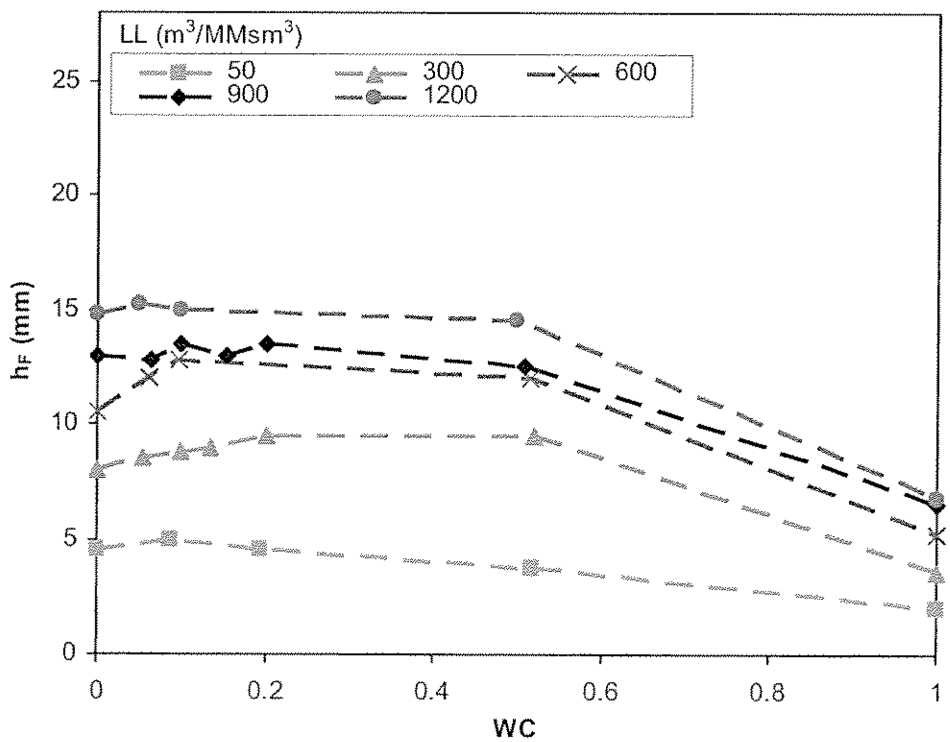

Figure 22: Total Film Thickness (v_{SG} = 15 m/s)

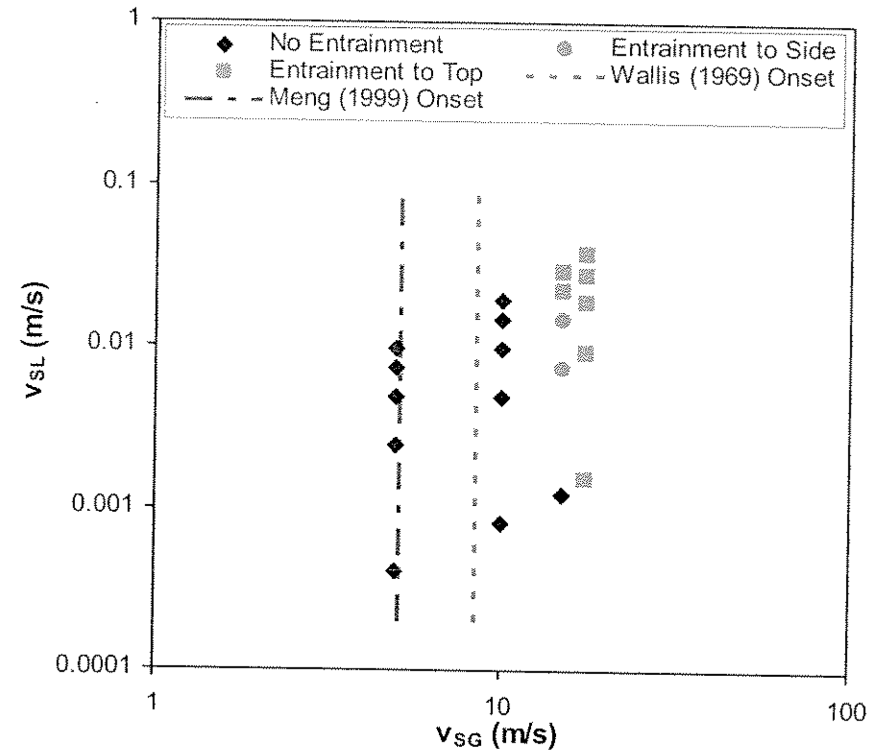

Figure 23: Onset Observation of Entrainment (Oil and Oil-Water)

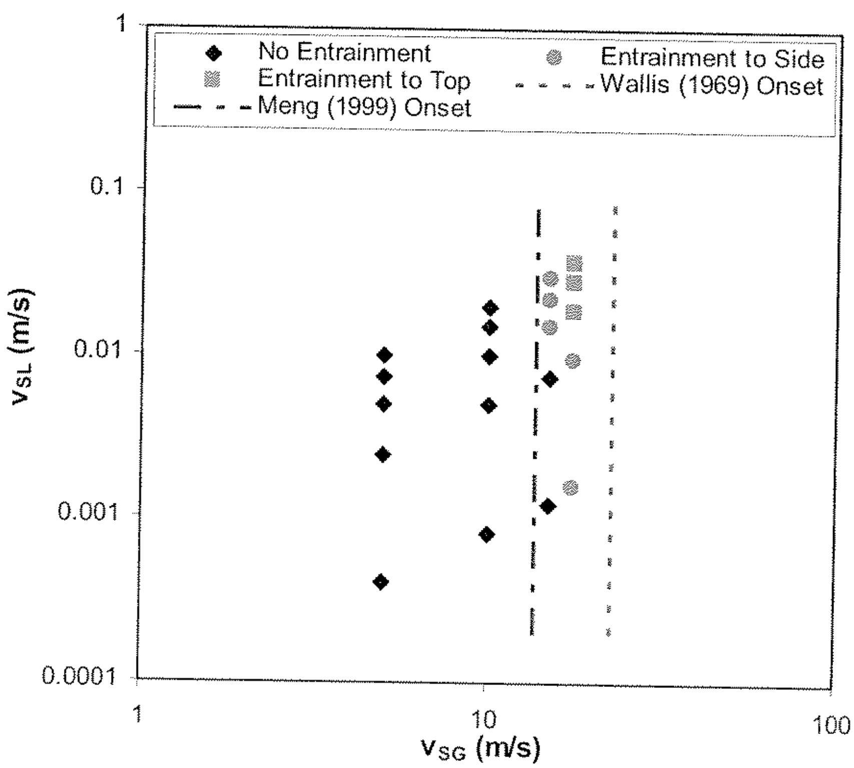

Figure 24: Onset Observation of Entrainment (Water)

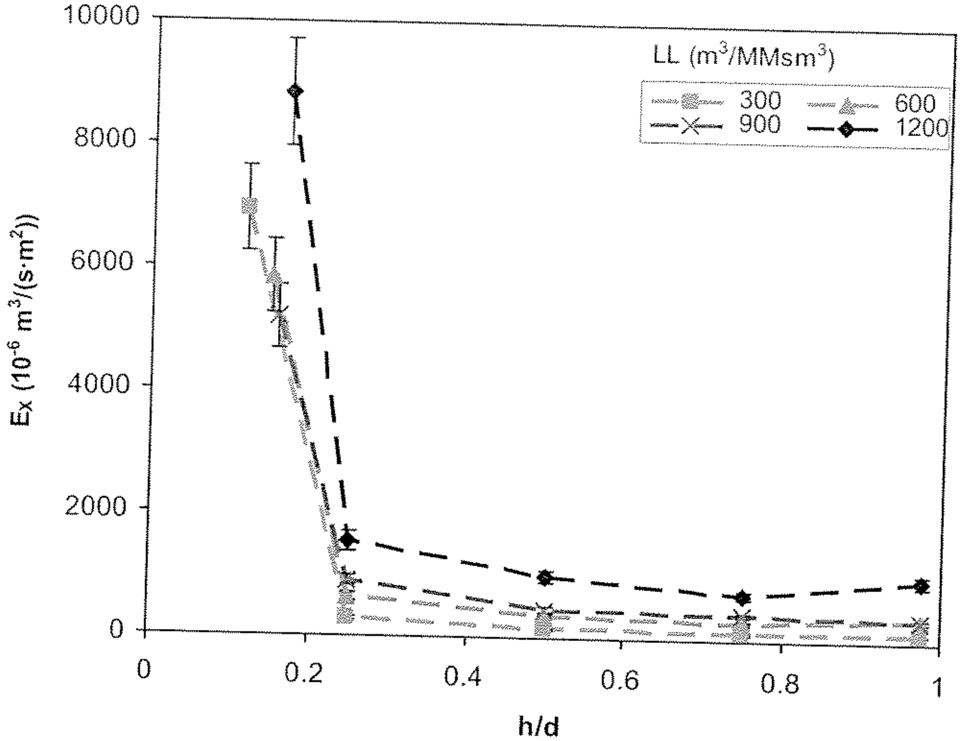

Figure 25: Total Liquid Entrainment flux Profile (v_{SG} = 17.5 m/s, WC = 0.15)

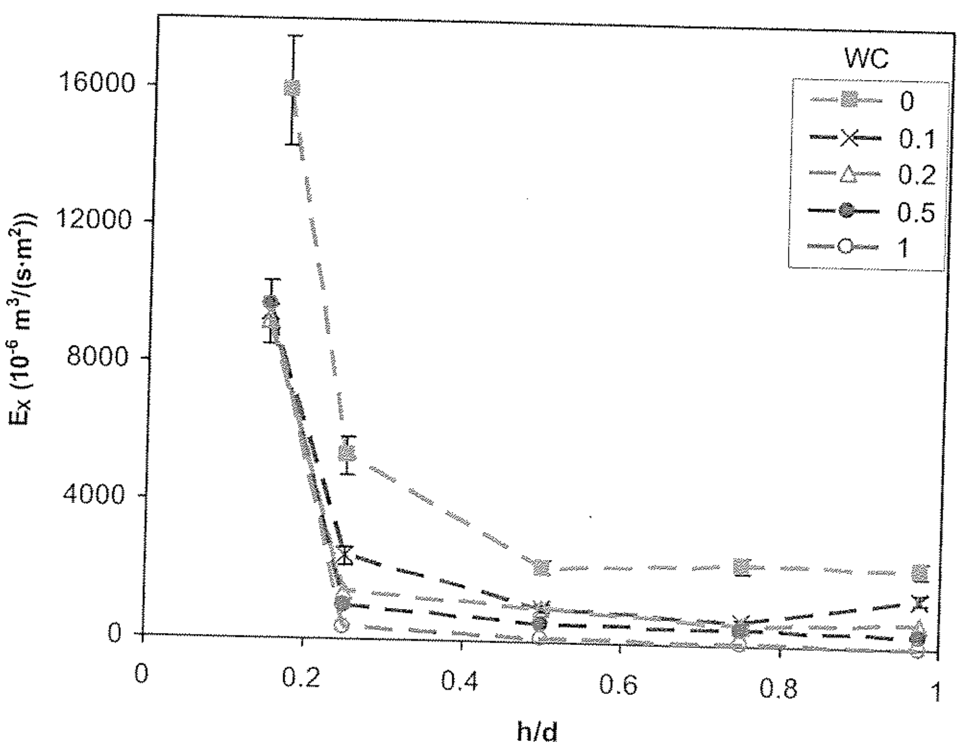

Figure 26: Total Liquid Entrainment Profile (v_{SG} = 17.5 m/s, LL = 1200 $m^3/MMsm^3$)

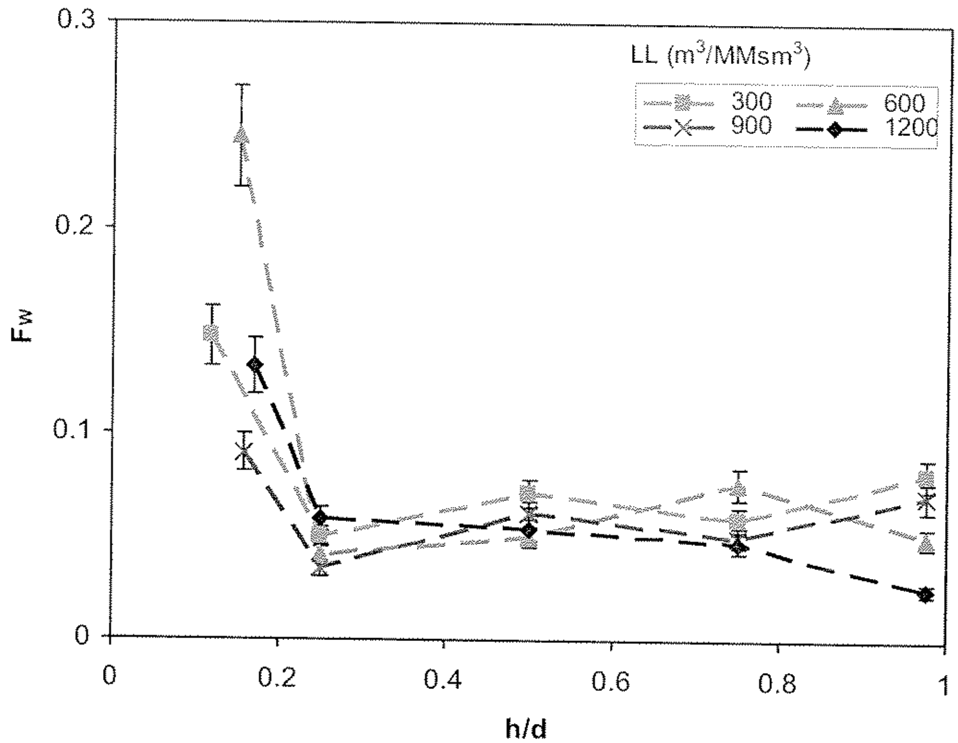

Figure 27: Water Fraction in Total Liquid Entrainment Profile (v_{SG} = 17.5 m/s, WC = 0.15)

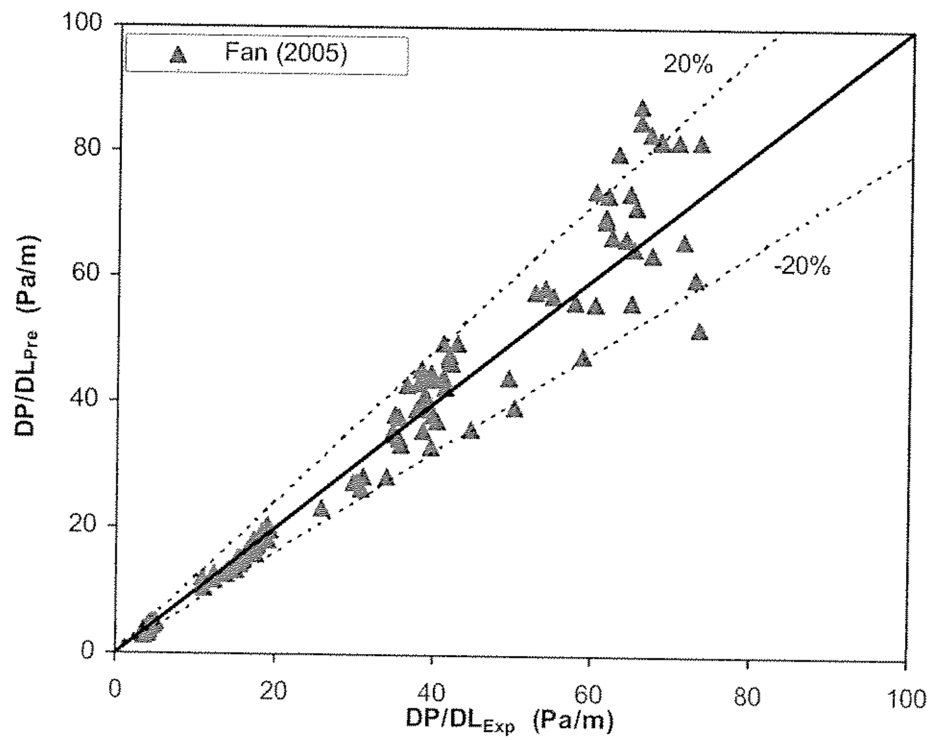

Figure 28: Comparison of Model Predictions and Measured Pressure Gradients

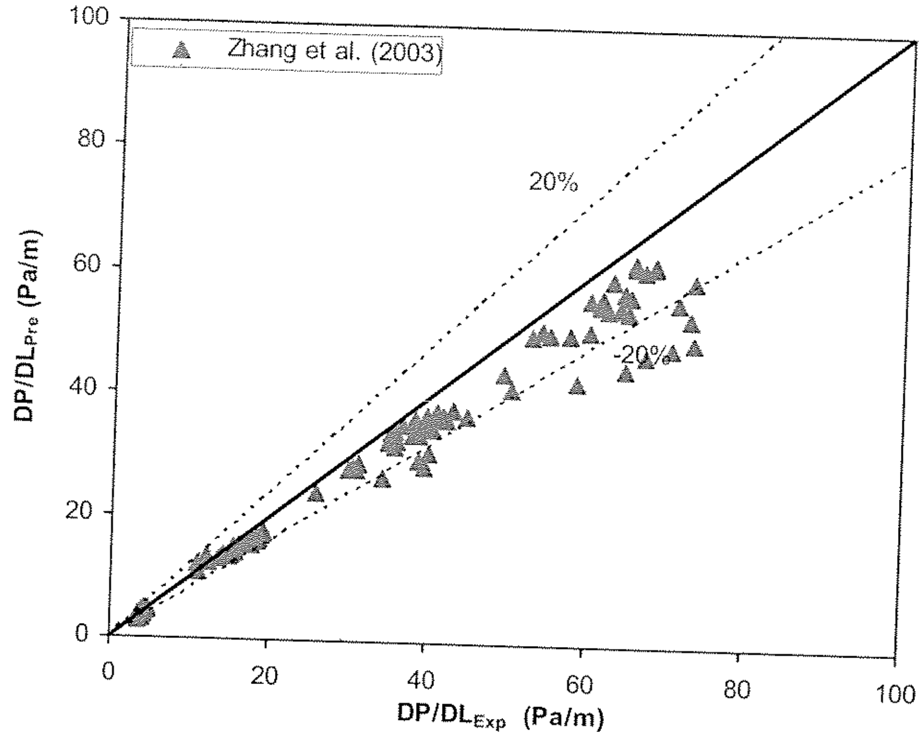

Figure 29: Comparison of Model Predictions and Measured Pressure Gradients

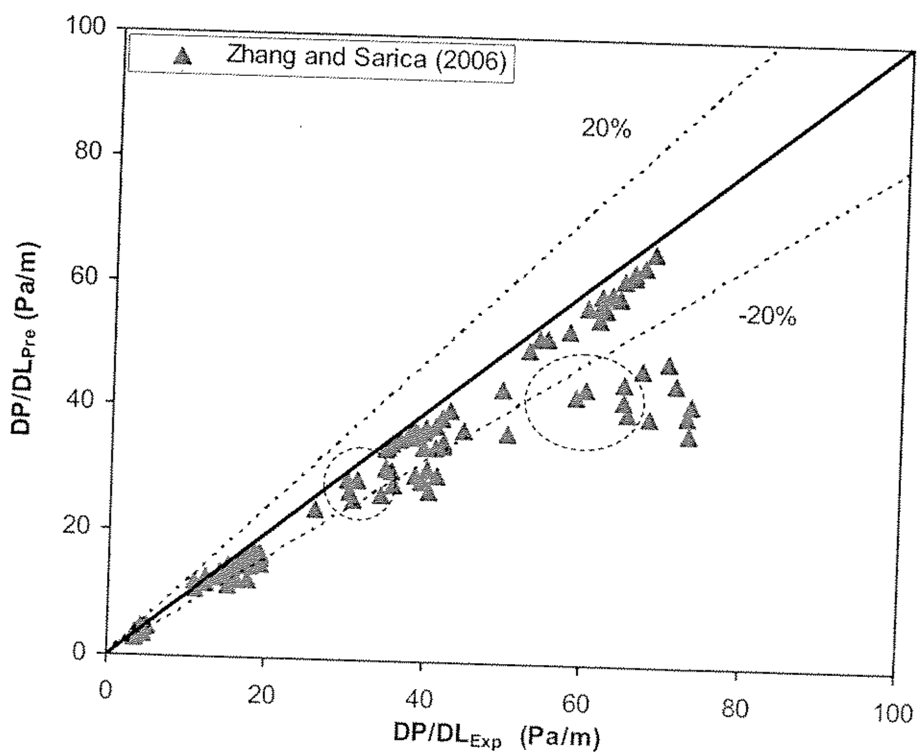

Figure 30: Comparison of Model Predictions and Measured Pressure Gradients

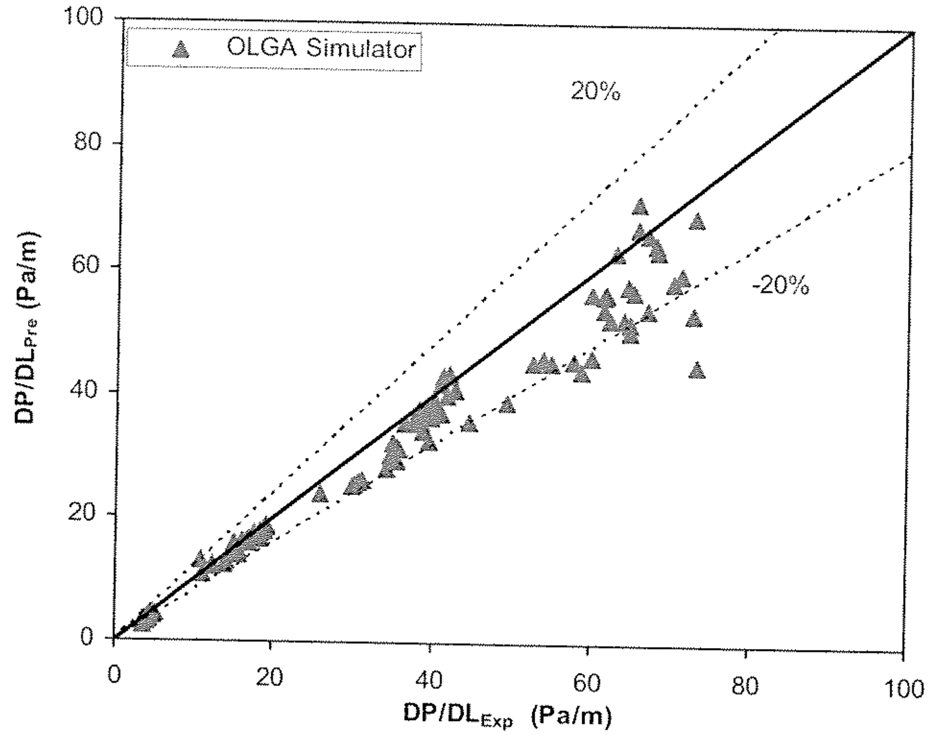

Figure 31: Comparison of Model Predictions and Measured Pressure Gradients

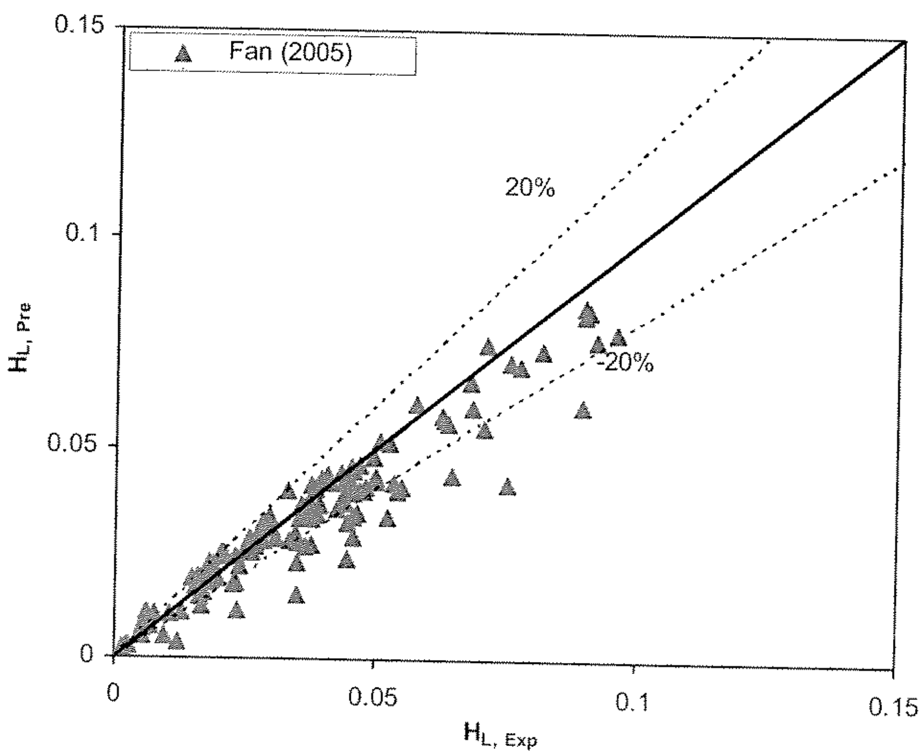

Figure 32: Comparison of Model Predictions and Measured Liquid Holdups

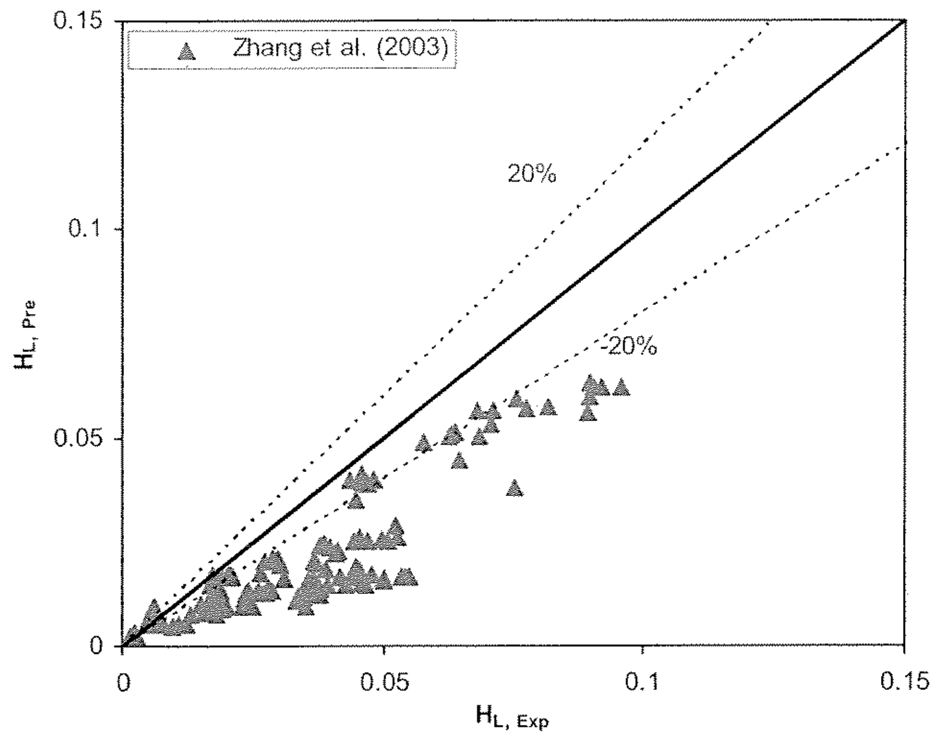

Figure 33: Comparison of Model Predictions and Measured Liquid Holdups

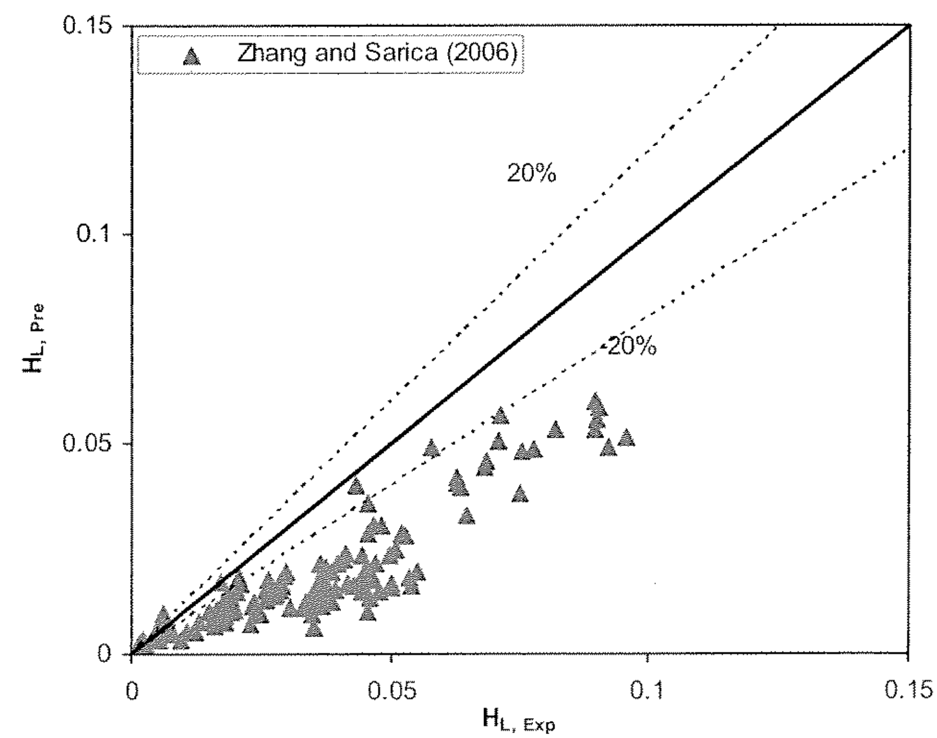

Figure 34: Comparison of Model Predictions and Measured Liquid Holdups

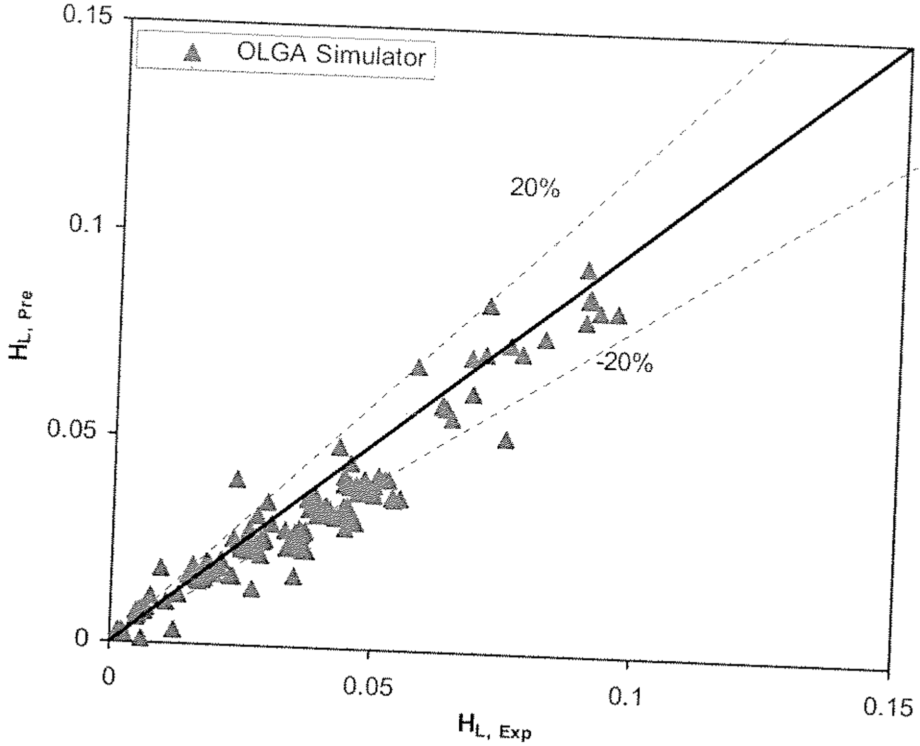

Figure 35: Comparison of Model Predictions and Measured Liquid Holdups

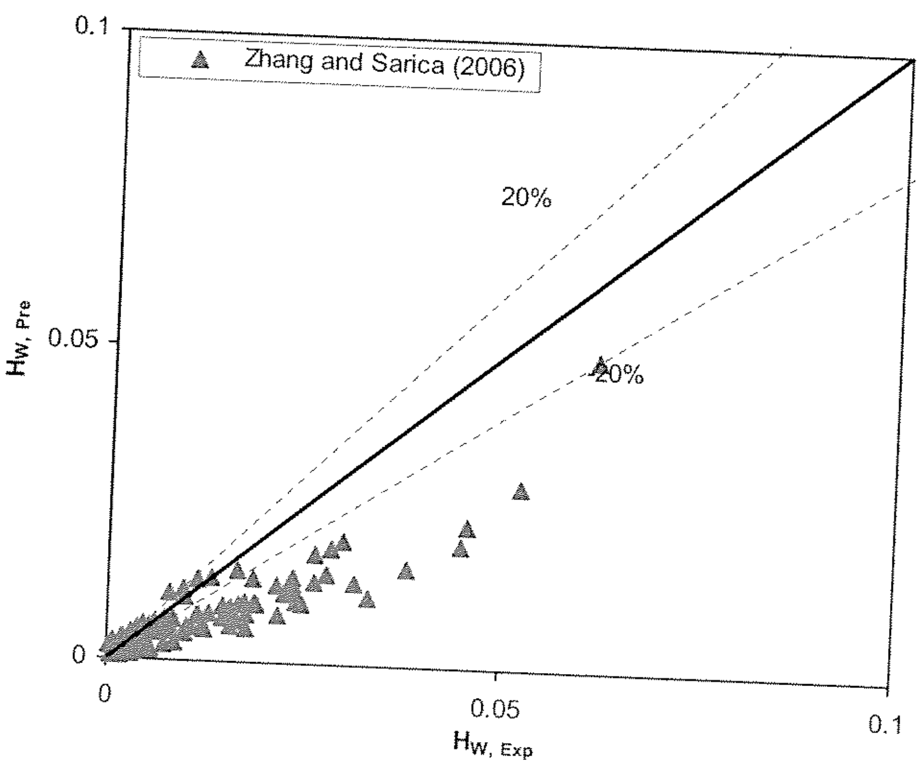

Figure 36: Comparison of Model Predictions and Measured Water Holdups

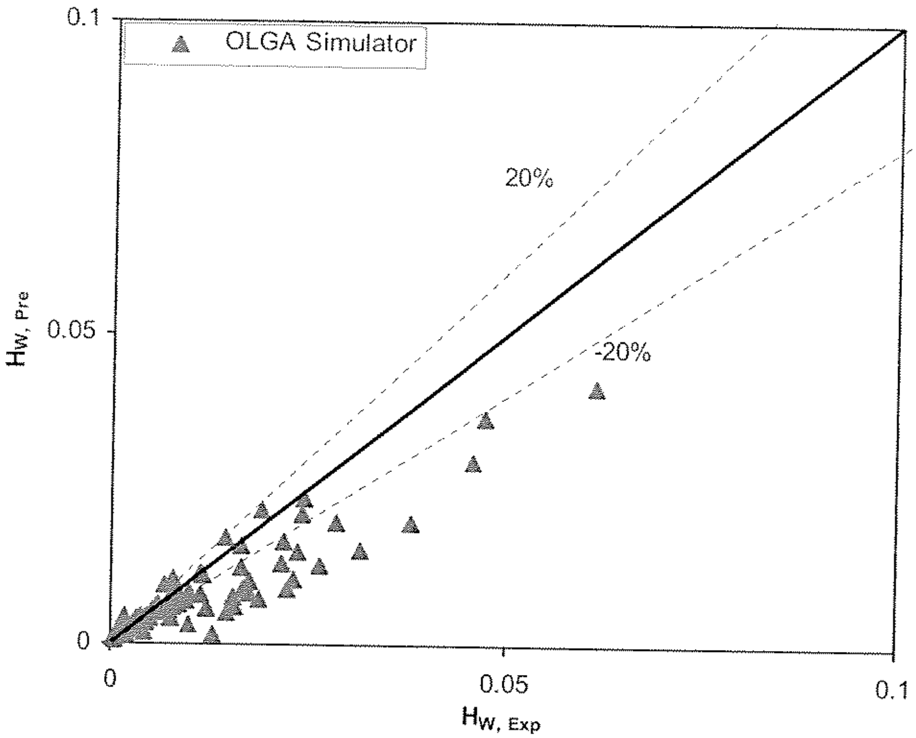

Figure 37: Comparison of Model Predictions and Measured Water Holdups

Table 1: Uncertainty Analysis

Parameter	Instrument	Random uncertainty (95%)	Systematic uncertainty (95%)	Combined uncertainty (95%)
Pressure	Rosemount pressure transducer	0.14%	1.20%	1.21%
Pressure drop	Rosemount differential pressure transducer	0.14%	1.20%	1.21%
Temperature	Rosemount temperature transducer	0.13 °C	0.5 °C	0.52 °C
Gas flow rate	Micro Motion flow meter	0.46%	0.35%	0.58%
Water flow rate	Micro Motion flow meter	0.13%	0.05%	0.14%
Oil flow rate	Micro Motion flow meter	0.13%	0.05%	0.14%
Wetted wall perimeter	Ruler	2 mm SS 3-5 mm SW	1 mm	2.2 mm SS 3.2-5.1 mm SW
Trapped oil volume	Quick-closing valve and graduated cylinder	N/A	1-5%	1-5%
Trapped water volume	Quick-closing valve and graduated cylinder	N/A	1-5%	1-5%
Water film thickness	Conductivity probe	1.5 mm SS 2.5-5 mm SW	1.0 mm	1.8 mm SS 2.9-5.2 mm SW
Oil film thickness	Conductivity probe	1.5 mm SS 2.5-5 mm SW	1.0 mm	1.8 mm SS 2.9-5.2 mm SW
Interfacial velocity	Thermo or dye tracer	8-15%	1%	8.1-15.1%
Liquid entrainment	Liquid entrainment sampling system	N/A	8%	8%

Table 2: Model Evaluation with Pressure Gradient Measurements

Model	Statistical Parameters					
	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4(Pa/m)	ε_5(Pa/m)	ε_6 (%)
Fan (2005)	1.070	8.879	11.235	1.088	3.451	5.752
Zhang et al. (2003)	-8.301	10.967	10.427	-3.638	3.776	4.875
Zhang and Sarica (2006)	-15.848	16.857	27.356	-5.351	5.411	8.691
OLGA	-13.099	13.862	25.356	-3.744	3.984	6.602

Table 3: Model Evaluation with Total Liquid Holdup Measurements

Model	Statistical Parameters					
	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (/)	ε_5 (/)	ε_6 (/)
Fan (2005)	-7.137	16.854	23.186	-0.004	0.005	0.007
Zhang et al. (2003)	-51.293	54.766	35.385	-0.015	0.015	0.011
Zhang and Sarica (2006)	-59.707	61.929	32.728	-0.017	0.017	0.011
OLGA	-11.706	21.284	26.701	-0.005	0.006	0.007

Table 4: Model Evaluation Using with Water Holdup Measurements

Model	Statistical Parameters					
	ε_1 (%)	ε_2 (%)	ε_3 (%)	ε_4 (/)	ε_5 (/)	ε_6 (/)
Zhang and Sarica (2006)	-42.353	56.238	48.921	-0.005	0.006	0.007
OLGA	-10.061	33.777	45.879	-0.003	0.004	0.006

Fluid Flow Projects

Low Liquid Loading Gas-Oil-Water Flow in Inclined Pipes

Feng Xiao

Advisory Board Meeting, November 6, 2007

Outline

- Objectives
- Introduction
- Preliminary Literature Review
- Facility and Modifications
- Experimental Study
- Project Schedule

Objectives

- Investigate Low Liquid Loading Three-phase Flow in Inclined Pipeline
- Acquire Data to Compare with Existing Model Predictions
- Suggest Modification for Existing Correlations or Develop New Model If Necessary

Fluid Flow Projects   Advisory Board Meeting, November 6, 2007

Introduction

- Low Liquid Loading Corresponds to Ratio of Liquid to Gas ≤ 1100 $m^3/MMsm^3$
- It Exists Widely in Wet Gas Pipeline
- Small Amount Liquid can Cause Significant Increase of Pressure Drop and Other Problems

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Preliminary Literature Review

- Stratified Flow Model
- Annular Flow Model
- TUFFP Low Liquid Loading Studies
- TUFFP Unified Model

Stratified Flow Model

- Taitel and Dukler (1976)
  - Analysis of Equilibrium Stratified Flow
- Cohen and Hanratty (1986)
  - Constant Interfacial Friction Factor
- Xiao et al. (1990)
  - Interfacial Friction Factor – Combination of Andritsos and Hanratty (1987) for Small Diameter Pipes and Baker et al. (1988) for Larger Diameter Pipes

Annular Flow Model

- Butterworth (1972)
  - Air-Water Annular Flow in a Horizontal Tube
- Jayanti et al. (1990)
  - Liquid Film Formation based the Shape of Disturbance Waves
- Williams et al. (1996)
  - Entrainment is Strongly Affected by Gas Velocity

TUFFP Low Liquid Loading Studies

- Chen (1997)
  - Air-oil, 0°, 77.9-mm ID pipe
- Meng (1999)
  - Air-oil, 0°, ±1°, ±2°, 2-in ID pipe
- Olive (2001)
  - Air-water, -1°, 2-in ID pipe
- Fan (2005)
  - Air-water, 0°, ±1°, ±2°, 2-in and 6-in ID pipes
- Dong (2007)
  - Air-oil-water, 0°, 6-in ID pipe

TUFFP Unified Model

- Zhang et al. (2003) Unified Model for Gas-Liquid Pipe Flow
- Zhang and Sarica (2006) Unified Model for Gas/Liquid/Gas Pipe Flow

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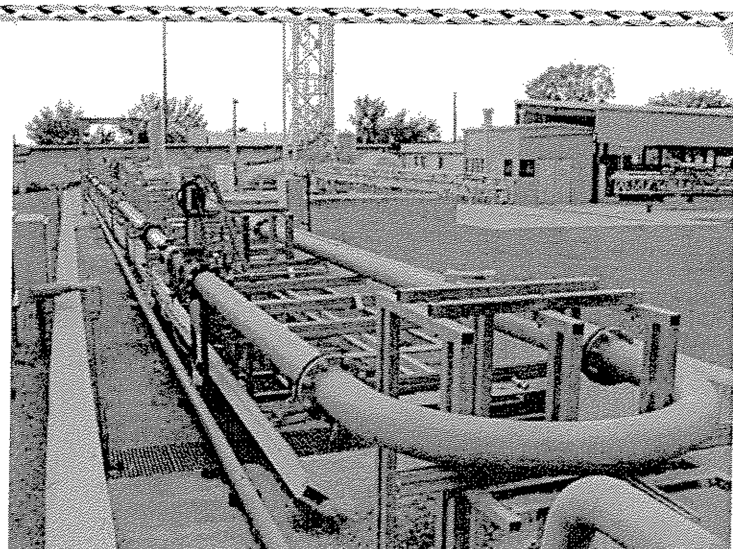
Facility



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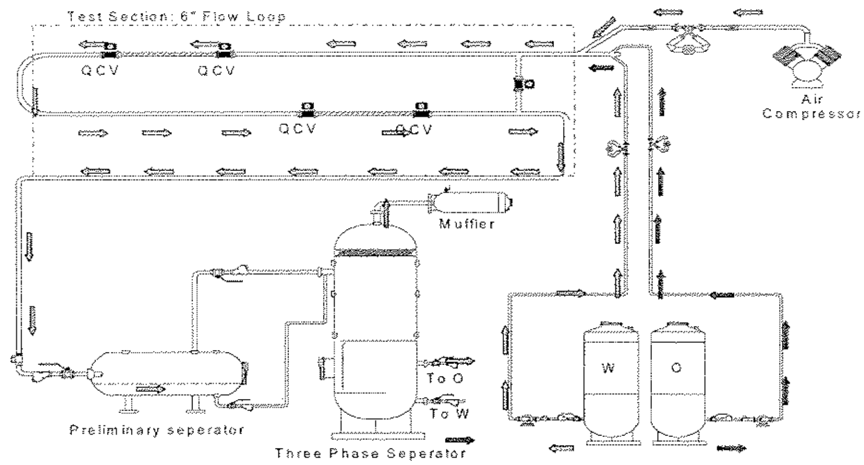
Facility ...



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Modifications

- Pipe Inclination Angles -2°, +2°
- Make Finer Grades on Pipe Inside Circumference
- Enhance Air Compressor Capacity
- Develop Information Storage Database to Store Test Data, Images, Videos and Comments

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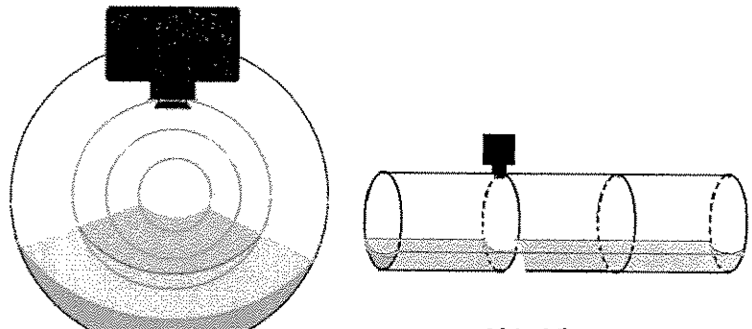
Advisory Board Meeting, November 6, 2007

Modifications

- Add Laser Sheet System for Gas-liquid Interface Shape Observation



Side View

Cross Sectional View

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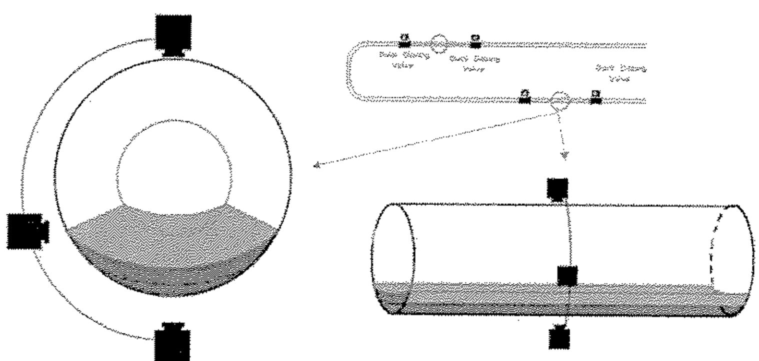
Modifications

- Use Real Time Camera Sets to Monitor Flow Development



Cross Sectional View

Side View

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Experimental Study

- Planned Measurements
- Preliminary Test and Main Test
- Test Matrix on Flow Pattern Maps

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Planned Measurements

- Pressure, Temperature, Pressure Gradient - PT and TT and DP
- Liquid Holdup - Quick Closing Valves and Pigging
- Wetted Wall Perimeter - Grades inside Pipe Circumference
- Liquid Entrainment Fraction - Iso-kinetic Sampling System

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Planned Measurements ...

- Liquid Film Thickness - Conductivity Probes
- Phase Continuity - Conductivity Probes
- Liquid Film Velocity - Warm or Cold Liquid Injection, Thermal Probes
- Cross Sectional Image - Cross-sectional Viewing System
- Flow Pattern Image - High Speed Camera

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Preliminary Test and Test

- Preliminary Test
  - Water Cuts: 0.0, 1.0; Inclination Angle: 0°
  - Validity and Repeatability, Establish Operation Procedures and Standards
- Test
  - Water Cuts: 0.0, 0.05, 0.1, 0.2, 0.5, 1.0; Inclination Angles: ±2°
- Test Matrix

Vsg (m/s)	Vsl (m/s)				
5	0.00025	0.0015	0.003	0.0045	0.006
10	0.0005	0.003	0.006	0.009	0.012
15	0.00075	0.0045	0.009	0.0135	0.018
20	0.001	0.006	0.012	0.018	0.024
25	0.00125	0.0075	0.015	0.0225	0.03

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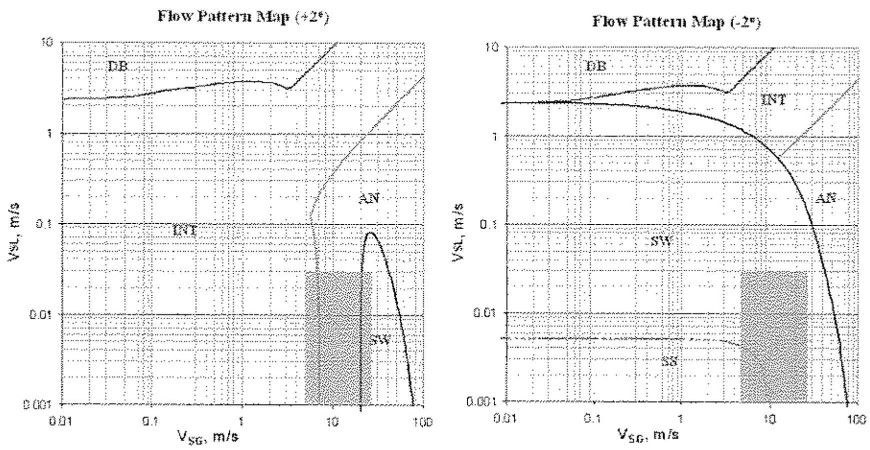
Test Matrix on Flow Pattern Maps



Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Project Schedule

- Literature Review — April 2008
- Facility Modifications — March 2008
- Preliminary Tests — April 2008
- Tests — September 2008
- Data Analysis and Final Report — December 2008

Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Low Liquid Loading Gas-Oil-Water Flow in Inclined Pipes

Feng Xiao

PROJECTE COMPLETION DATES:

Literature Review....April 2008
Facility Modification ....March 2008
Preliminary Testing....April 2008
Testing ....September 2008
Model Development....November 2008
Final Report ....December 2008

Objectives

The main objectives of this study are to experimentally investigate low liquid loading gas-oil-water flow in inclined pipes, to evaluate the existing models with experimental data and to suggest modifications or new developments for the models if necessary.

Introduction

Low liquid loading gas-oil-water flow exists widely in wet gas pipelines. These pipelines often contain water and hydrocarbon condensates, and small amounts of condensates can lead to a significant pressure loss along a pipeline. Many issues like hydrate formation, pigging frequency and downstream facility design are dependent on the pressure and holdup predictions in the pipeline. Therefore, understanding of the flow characteristics of low liquid loading gas-oil-water flow is of great importance in transportation of wet gas. Due to the differences in fluid properties, oil and water may exhibit significant different behaviors than single phase liquid. However, very few studies have been conducted on low liquid loading three-phase flow, probably due to the complexity and uncertainty. Although several authors have published papers on three-phase flow pattern and modeling of three-phase flow, most of them do not cover the range of low liquid loading flow.

In this study, low liquid loading gas-oil-water flow experiments will be conducted in an inclined 6-in ID flow loop. The flow pattern, pressure drop, fractions of the three phases, liquid film thickness, wetted wall fractions and entrainment fractions will be observed and measured at different flow rates, liquid loading levels and water cuts. The pipe inclination angles will be $\pm 2°$.

Literature Review

Although many theoretical and experimental investigations on gas-liquid pipe flow have been carried out, just a few studies were focused on low liquid loading, and even fewer on three-phase flow with low liquid loading. However, it is in this domain that natural gas with condensates is transported in gas transmission pipelines.

The most commonly encountered flow patterns in low liquid loading pipelines are stratified flow and annular flow. The literature review focuses on stratified and annular flow studies in horizontal and near-horizontal pipes, three-phase flow models, as well as recent studies on low liquid loading multiphase flow.

Stratified flow is the most dominant flow pattern for low liquid loading pipe flow in near-horizontal pipelines, particularly in downward inclined sections. The Taitel and Dukler (1976) model for flow-pattern prediction presents an analysis of the equilibrium stratified flow. If the flow is found to be stable, stratified flow exists. The original equilibrium stratified flow analysis was carried out assuming smooth interface and that interface shear stress is the same as the gas-wall shear stress. However, for actual stratified flow, the interfacial shear stress may be different. For stratified wavy flow with small amplitude waves, a constant interfacial friction factor, 0.0142, was suggested by Cohen and Hanratty (1968). Xiao et al. (1990) suggested using a combination of the Andritsos and Hanratty (1987) correlation for small diameter pipes and the Baker et al. (1988) correlation for larger pipe diameters to predict the interfacial friction factor.

Annular flow is also important for low liquid loading pipe flow study. Butterworth (1972) studied air-water annular flow in a horizontal tube. The film characteristics were measured as a function of circumferential position, and liquid entrainment measurements were made in the gas core. Jayanti et al. (1990) proposed a new mechanism base on the shape of disturbance waves in the prediction of the film thickness distribution for transporting liquid from the bottom to the top of the pipe. Williams et al. (1995) observed a stratification of droplets because of the influence of gravity, and also showed that entrainment increases strongly with increasing gas velocity.

Chen et al. (1997) studied tow-phase horizontal pipe flow with low liquid lading. The pipe ID was 77.9 mm. Air and Kerosene were used as working fluids. The gas-liquid interface usually exhibited a concave shape. The liquid film-wetted wall fraction, liquid holdup, and pressure drop were measured. A mechanistic "double-circle" model and a correlation of interfacial friction factor were proposed.

Meng (1999) investigated the low liquid loading flow in horizontal and near horizontal pipelines. The inclination angles included -2°, -1°, 0°, +1°, +2°. The pipe ID was 50.1 mm. The test fluids were air and oil. The gas and liquid superficial velocities ranged from 5 to 25 m/s and from 0.001 to 0.053 m/s, respectively. The measurements included liquid film flow rate, pressure drop, liquid holdup and droplet deposition rate.

Olive et al. (2003) conducted low liquid loading two-phase experiments in a 2-in ID near-horizontal pipe using water as the liquid phase. The results were compared with Meng's (1999) measurements. At certain superficial gas velocities and relatively high liquid loadings, an increase of superficial gas velocity led to an increase of the liquid holdup. The possible reasons for these phenomena were discussed by the authors.

Fan (2005) studied the low liquid loading two-phase flow by experiments and modeling. Using air and water as the working fluids, the experiments were conducted on two different flow loops of 2-in ID and 6-in ID. Several models were evaluated with the experimental data, finding that most models could not give good predictions of pressure drop and liquid holdup, especially for the 6-in ID data. A mechanistic model for low liquid loading two-phase flow was developed to predict the pressure gradient and liquid holdup.

Zhang and Sarica (2005) proposed a unified model for the prediction of gas-oil-water flow behavior in wellbores and pipelines. This model describes three-phase flow based on two criteria: gas-liquid flow pattern and oil-water mixing status. The three-phase flow was treated as gas-liquid two-phase flow if the two liquids are fully mixed or as a three-layer stratified flow at low flow rates in horizontal or slightly inclined pipes. Closure relationships describing the distribution between the two liquid phases were proposed. Experimental data of gas-oil-water pipe flow were used to evaluate the model.

Dong (2007) investigated the low liquid loading gas-oil-water flow in a 6-in ID horizontal pipe. The gas-liquid flow patterns and oil-water distributions were observed and many flow parameters were measured, including pressure gradient, liquid holdups, wetted wall fractions, film thickness and entrainment profile. Several models were evaluated with the experimental data, and modifications were suggested.

Experimental Study

Experimental Facility and Flow Loop

The experimental facility for this study is the 6-in flow loop which has been used to conduct research on low liquid loading flow for several years. The test section is made of 6-in ID pipes and consists of two runs connected with a U-shape bend. Each run is a 56.4-m long steel pipe with an acrylic visual section at the end of it. For liquid, especially oil holdup measurement, a pigging system has been installed on the first run, with which the liquid holdup can be measured accurately and quickly (Dong, 2007).

The inclination angle of the test section can be changed from 0° to 2°, making it possible to have downward flow with inclination angle down to -2° and upward flow with inclination angle up to +2° with the two runs, respectively.

Instrumentation and Data Acquisition

The instrumentations are designed based on the desired parameters: flow rates of three phases, temperature, pressure, pressure drop, oil and water holdups, wetted wall perimeter, liquid entrainment in gas phase, liquid film thickness, phase continuity and liquid film velocity. The cross sectional images and flow pattern images will also be required. All the current instrumentation and the DeltaV™ digital acquisition system will be used in the upcoming tests. Please refer to Dong (2007) for details.

Anticipated Modifications

The pipe inclination angle will be changed. The first run of the loop will be changed to +2°, while the second run to -2°. This way, the upward and downward flow experiments can be carried out simultaneously

Finer grades inside the pipe circumference need to be made to obtain more accurate measurements of wetted wall perimeters.

The capacity of the air compressor needs to be increased. The current air compressors can supply up to 17.5 m/s superficial gas velocity. Higher superficial gas velocity is needed to study the entrainment and annular flow behaviors.

A laser sheet system for acquisition of the gas-liquid interface shape will be added. The existing cross sectional view system failed to obtain a clear shape of the interface. A laser sheet can illuminate the liquid with some fluorescence. The difference of the brightness between liquid and gas can depict a clear liquid interface (see Fig. 1).

The real time camera sets will be placed on the flow loop. The initial plan is to place 3 monitors on each run, as shown in Fig. 2. Those cameras are expected to enhance test efficiency by monitoring the flow development from the computer room.

VBA will be used to develop an Information Storage Database to store test data, images, videos and comments. There are 150 cases for each inclination angle and each case contains 17 parameters and several images. It is necessary to use a tool to arrange so much information logically and orderly. It will be easier and quicker to demonstrate and analyze those data. VBA facilitates the execution of complicated operations/usages within Excel, which offers plenty of database features and can be combined with other database software such as Access, FoxPro and SQL Server.

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 is selected as the oil phase. The physical properties of the oil are given below.

- 33.2 API gravity
- 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 against water: 16.38 dynes/cm @ 25.1 °C
- Pour point temperature: -12.2 °C
- Flash point temperature: 185 °C

Testing Range

In this study, the proposed superficial gas velocity ranges from 5 m/s to 25 m/s with a step of 5 m/s. The liquid loading level ranges from 50-1200 m^3/MMsm^3. The water cut changes from 0 to 100%. Inclination angles will be -2 ° and +2° from horizontal. Figure 3 shows the gas-liquid test matrices on the flow pattern maps generated using the Taitel and Dukler model (1976).

Project Schedule

- Literature review – April 2008
- Facility modifications – March 2008
- Preliminary tests – April 2008
- Tests – September 2008
- Data analysis and final report – December 2008

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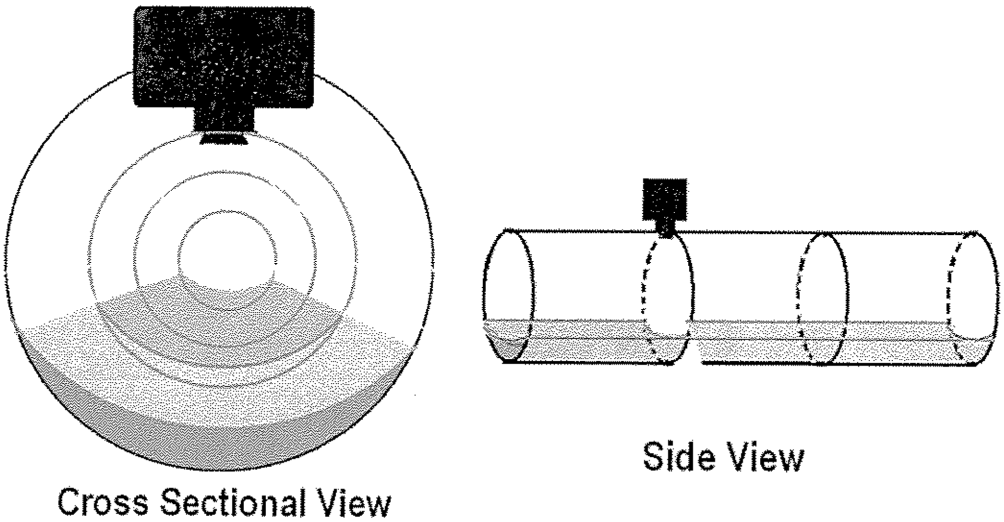


Figure 1: Laser Sheet System

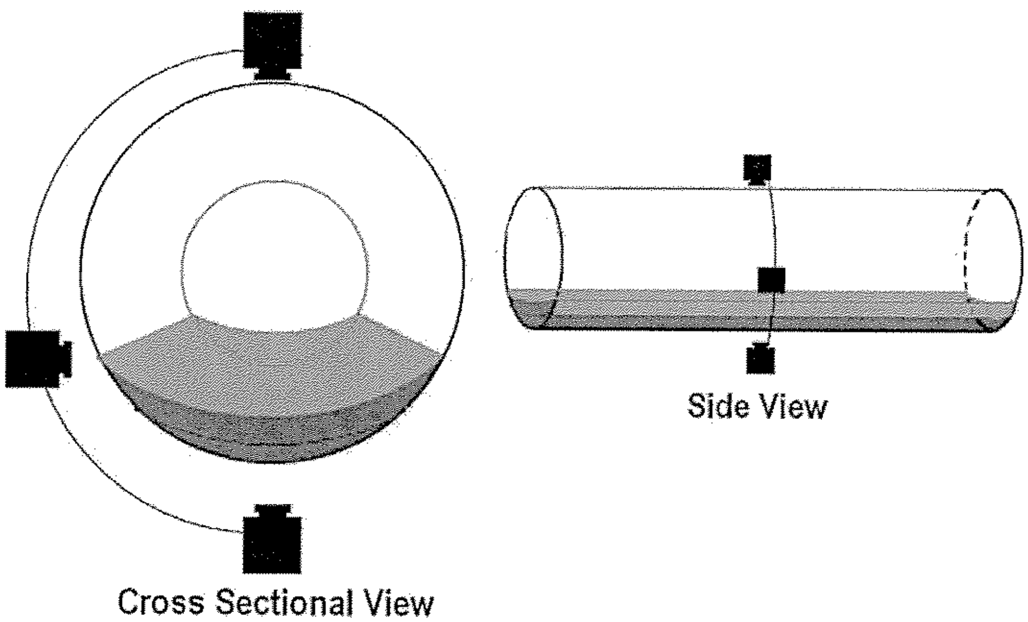
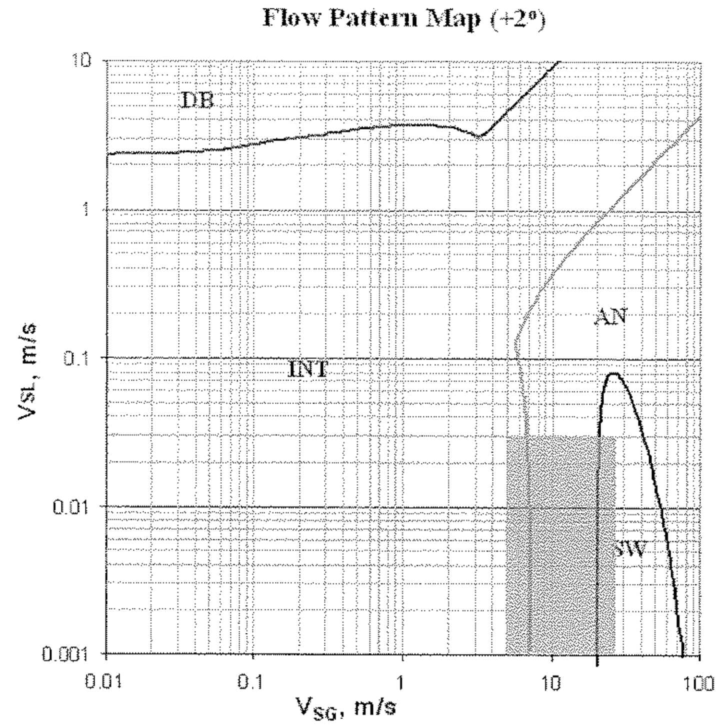


Figure 2: Real Time Camera Set



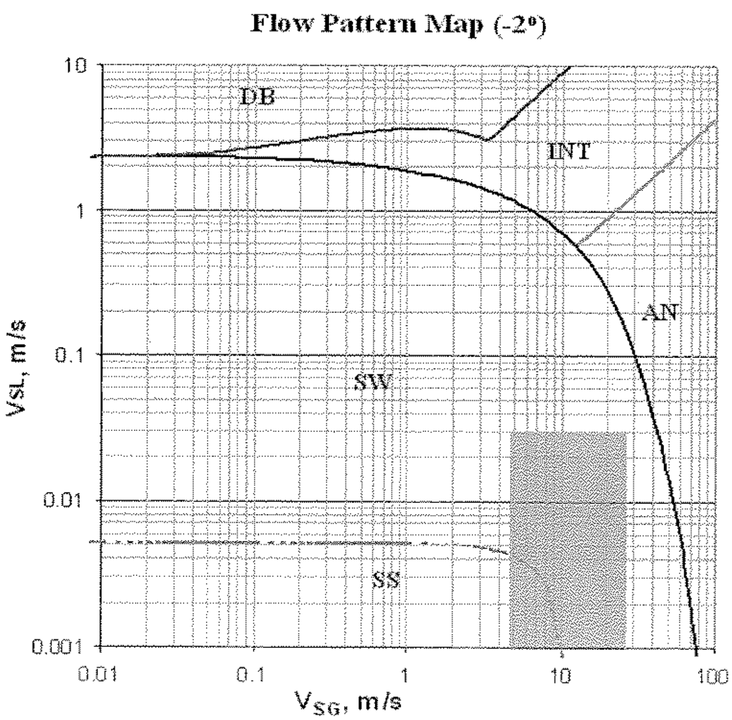


Figure 3: Test Ranges on Flow Pattern Maps

Fluid Flow Projects

New Dimensionless Parameters and a Power Law Correlation for Pressure Drop of Gas-Liquid Flows in Horizontal Pipelines

Al-Sarkhi Abdel

Advisory Board Meeting, November 6, 2007

Outline

- Objectives
- Introduction
- Theory
- Comparison with Experimental Data
- Conclusions

Objectives

- New Dimensionless Parameters
- Simple and Quick Correlation to Predict Pressure Drop During Gas-Liquid Flow in Horizontal Pipes

Introduction

- Compared to Single Phase Flow, Two-phase Flow
  - More Complex
  - Different Patterns
  - Few Relevant Dimensionless Numbers
- Finding Dimensionless Parameters to Simplify Correlations and Models is Extremely Important

Introduction

- Correlations
  - Successful in Prediction Pressure Drop for Certain Flow Conditions Only
  - Constructed With Large Number of Constants and Parameters Which Make Them Inconvenient to be Easily Used
  - Based on Using Different Plots or Equations for Different Conditions
    - Flow Pattern, Superficial Velocities, Pipe Diameter, Gas and Liquid Densities, Etc.

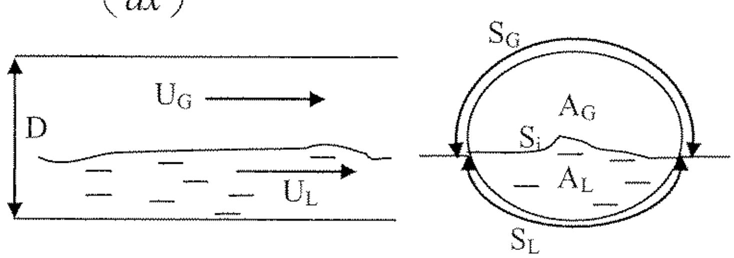
Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Theory

1. Stratified Flow

$$-A_L\left(\frac{dP}{dx}\right)-\tau_{WL}S_L+\tau_i S_i=0 \quad \text{(1) Liquid Momentum}$$

$$-A_G\left(\frac{dP}{dx}\right)-\tau_{WG}S_G-\tau_i S_i=0 \quad \text{(2) Gas Momentum}$$



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Theory - *Stratified Flow ...*

- **Assuming Gas and Liquid Pressure Gradients are Same at a Given Pipe Cross Section and by Adding Eqs. 1 and 2**

$$\frac{dP}{dx} = \frac{-1}{A_L + A_G}\left[\tau_{WG} S_G + \tau_{WL} S_L\right] \qquad (3)$$

$$\tau_{WL} = f_L \frac{\rho_L U_L^2}{2} \qquad \tau_{WG} = f_G \frac{\rho_G U_G^2}{2}$$

Liquid shear stress   **Gas shear stress**

Theory - *Stratified Flow ...*

- **Multiplying by, D, and Dividing by The Dynamics Pressure of Liquid Eq. 3 Becomes**

$$\frac{(dP/dx)D}{\frac{1}{2}\rho_L U_{SL}^2} = D\frac{-A_P}{A_L^2}\left\{S_L f_L + S_G f_G \frac{\rho_L}{\rho_G}\frac{U_G^2}{U_L^2}\right\} \qquad (4)$$

- **Dynamic Pressure of Liquid =** $1/2\rho_L U_L^2$
- **Dimensionless Pressure Drop Parameter**

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

Theory - *Stratified Flow ...*

- The Other Dimensionless Parameter, *X**, is a Ratio of Modified Superficial Liquid Froude number, Fr_L, to Modified Superficial Gas Froude Number, Fr_G

$$\frac{Fr_L}{Fr_G} = \frac{\sqrt{\frac{\rho_L}{\rho_L - \rho_G}} \frac{U_{SL}}{\sqrt{Dg\cos\alpha}}}{\sqrt{\frac{\rho_G}{\rho_L - \rho_G}} \frac{U_{SG}}{\sqrt{Dg\cos\alpha}}}$$

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Theory - *Stratified Flow ...*

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

- Using the Parameter, *X**, Eq. (4) can be Rewritten As:

$$P^* = -D\frac{A_P}{A_L^2}\left\{S_L f_L + S_G f_G \left(\frac{A_L}{A_G}\right)^2 X^{*-2}\right\} \quad (5)$$

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Theory - *Stratified Flow*

- Using the Following Dimensionless Parameters (D as a Length Scale)

$$S_L^* = \frac{S_L}{D} \qquad S_G^* = \frac{S_G}{D} \qquad A_L^* = \frac{A_L}{D^2} \qquad A_G^* = \frac{A_G}{D^2}$$

- Eq. (5) can be Rewritten as:

$$P^* = -\frac{\pi}{4}\left\{\frac{S_L^* f_L}{A_L^{*2}} + \frac{S_G^* f_G}{A_G^{*2}} X^{*-2}\right\} \qquad (6)$$

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Theory - *Stratified Flow*

- Thus, P^* is a Function of X^* and other Parameters (S_L, f_L,f_G, D, A_L, A_G, S_G) which can be Expressed as Unique Functions of Liquid Holdup (H_L)
- There is a Unique Relationship Between P^*, X^* and H_L

$$P^* = -\frac{\pi}{4}\left\{\frac{S_L^* f_L}{A_L^{*2}} + \frac{S_G^* f_G}{A_G^{*2}} X^{*-2}\right\} \qquad (6)$$

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Theory

2. Annular Flow

- Following the Same Analysis Above, The Liquid Momentum Equation, Eq. (1) Can Also be Written for Annular Flow as,

$$\frac{(dP/dx)D}{\frac{1}{2}\rho_L U_{SL}^2} = D\left(\frac{A_P}{A_L}\right)^2 \times \left\{-\frac{S_L f_L}{A_L} + \frac{S_i f_i}{A_L}\frac{\rho_G}{\rho_L}\frac{(U_G - U_L)^2}{U_L^2}\right\} \quad (7)$$

$$\tau_i = f_i \frac{\rho_G (U_G - U_L)^2}{2}$$

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Theory – *Annular Flow ...*

- For Annular Flow, Last Term in Eq. (7) Can be Approximated as

$$U_L << U_G \qquad (U_G - U_L)^2 \approx U_G^2$$

- Using Same Dimensionless Parameters Defined Above, Eq. (7) Can be Simplified As,

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

Again ...

$$P^* = \Gamma(S_L, f_L, f_I, D, A_L, A_G, S_G, X^*) = \Gamma(X^*, H_L)$$

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Comparison with Experimental Data

- P^* *vs.* X^* Correlation Tested Against 1300 Published Experimental Data Points
- Data Covers
  - Stratified-Smooth, Stratified-Wavy, Stratified-Atomization, Stratified-Annular-Transition and Annular Flow Patterns
  - Different Inclination Angle, Various Liquid and Gas Viscosities, Pipe Diameter, Pipe Type and Pressure
- P^* *vs.* X^* Behavior is Self-Similar

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Comparison with Experimental Data

- All Published Pressure Drop Data Follows a Power Law Behavior for Values of $X^* < 0.3$ (Equivalent to Liquid Loadings < 9750 $m^3/MMsm^3$, Which Can be Written As,

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

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Evaluation of Power Law Equation

Data Source	Pipe-ID (m)	Angle	A	B	R^2
Fan (2005)	0.1524	0	0.0576	-1.7838	0.9988
Fan (2005)	0.1524	2	0.1115	-1.6504	0.9897
Fan (2005)	0.1524	-2	0.038	-1.8761	0.9994
Fan (2005)	0.0501	0	0.0587	-1.8328	0.9944
Fan (2005)	0.0501	2	0.0884	-1.7625	0.9921
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Meng et. al (2001)	0.0501	-1	0.0001	-1.8195	0.9999
Chen et al. (1997)	0.078	0	0.0909	-1.7285	0.9951

*Note: Only data with X^*>0.3 has the values of R^2<0.98

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Evaluation of Power Law Equation

Data Source	Pipe-ID (m)	Angle	A	B	R^2
Paras et al(1994)	0.051	0	0.1337	-1.6826	0.9872
Kokal (1987)	0.0762	0	0.2393	-1.1329	0.9435*
Kokal (1987)	0.0762	-9	0.0651	-1.5695	0.9272*
Kokal (1987)	0.0762	-5	0.0683	-1.4971	0.9350*
Andritsos (1986)	0.095	0	0.1189	-1.8737	0.9889
Andritsos (1986)	0.025	0	0.2301	-1.6287	0.9809
Mukherjee (1979)	0.0381	0	0.0366	-1.964	0.9788
Cheremisinoff (1977)	0.063	0	0.0964	-1.7666	0.9740
Beggs & Brill (1973)	0.025	0	0.678	-0.9639	0.9393*
Beggs & Brill (1973)	0.025	10	0.9017	-0.8887	0.9017*
Beggs & Brill (1973)	0.025	-10	0.5257	-0.9614	0.9199*
Beggs & Brill (1973)	0.0381	0	0.4799	-1.1338	0.9697
Beggs & Brill (1973)	0.0381	10	1.0769	-1.1085	0.9270*
Beggs & Brill (1973)	0.0381	-10	0.3224	-1.2549	0.9740

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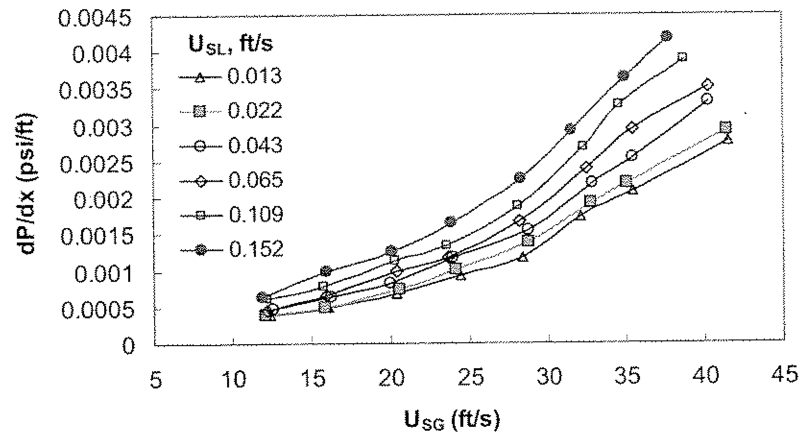
Chen et al. (1997) Data for Air and Kerosene in 3 in. Pipe

Example 1



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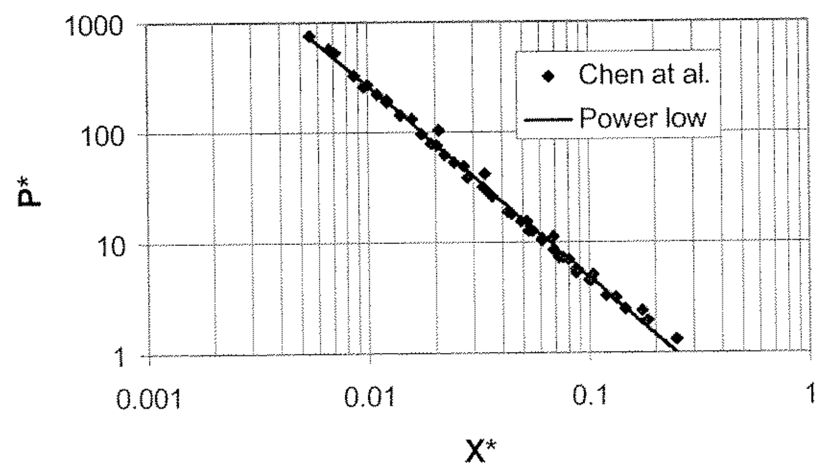
Chen et al. (1997) Data for Air and Kerosene in 3 in. Pipe

Example 1:



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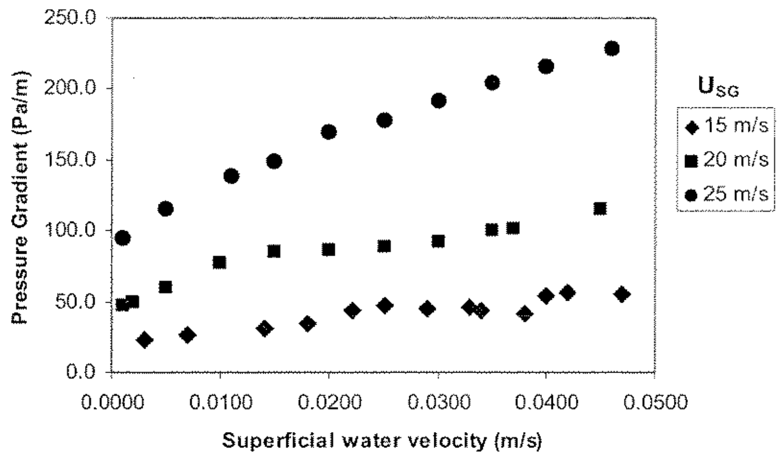
Badies et al. (2000) Air and Water in 0.079 m ID Pipe (Stratified Wavy Flow)

Example 2:



Badies et al. (2000) Air and Water in 0.079 m ID Pipe (Stratified Wavy Flow)

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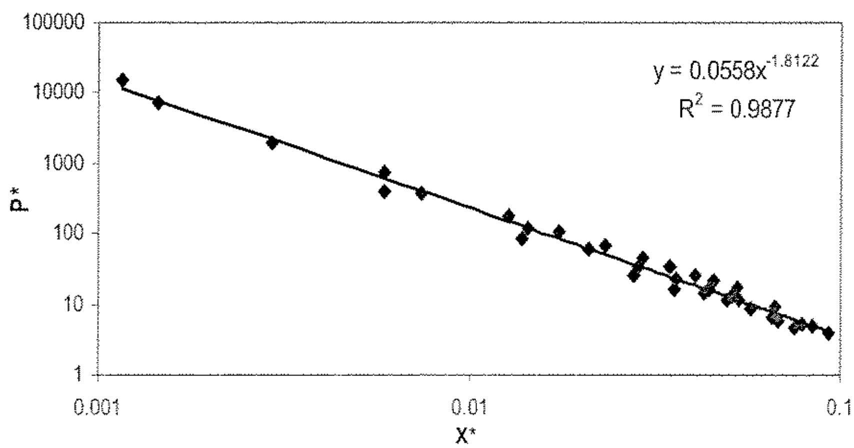
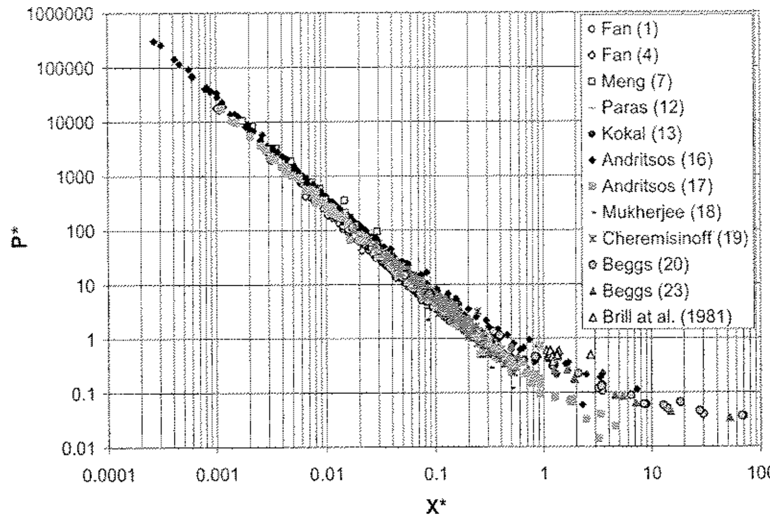


Power Law Evaluation: Published Data for Gas-Liquid in Horizontal Pipelines



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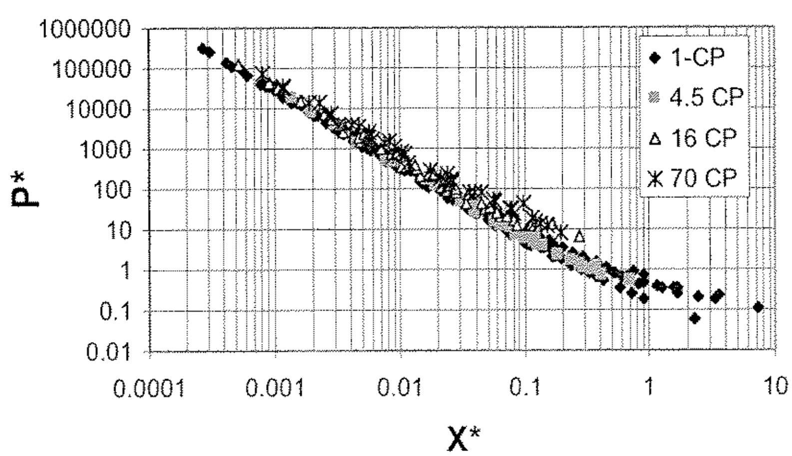
Andritsos (1986) Data of Air and Glycerin Solution 0.0254-m Pipe

Different Viscosity



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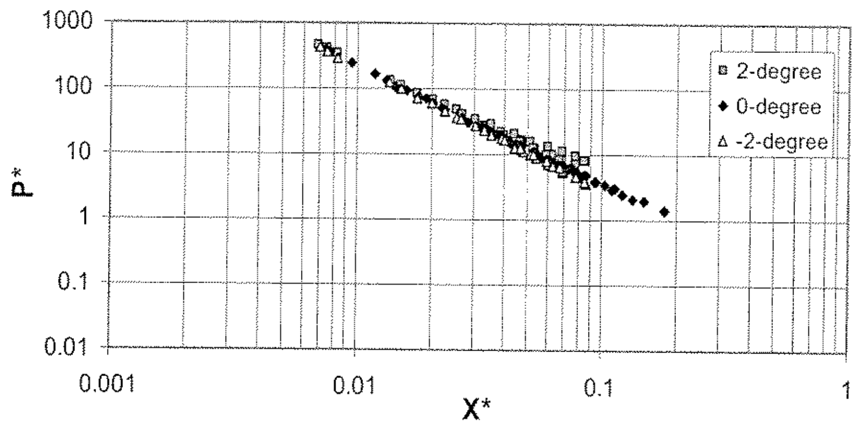
Fan (2005) Data for Air and Water in 0.1524 m Pipe

Different Inclination



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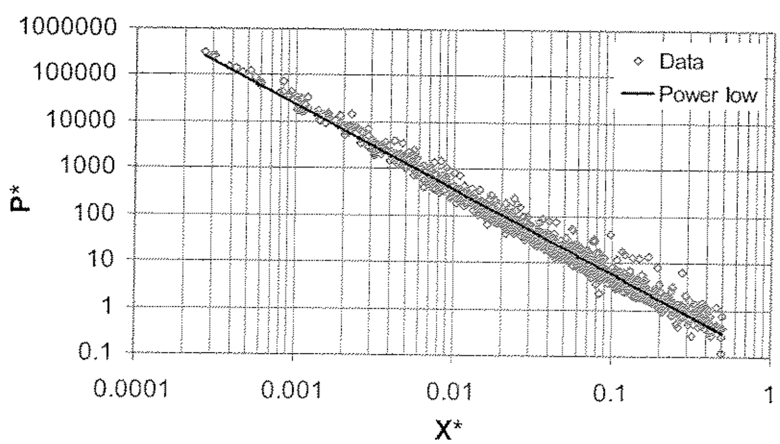
Approximate Universal Power Law Equation Gas-Liquid Flows in Horizontal Pipes

$$P^{*} = 0.0895 X^{*-1.8106}$$



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Conclusions

- Power Law Fits Very Well All Published Data For $X^* < 0.3$ (LL = 9570 $m^3/MMsm^3$)
- Pressure Drop Can be Predicted by Knowing The Mass Flow Rates
- Simplicity In Presenting And Correlating Many Of The Data Points In A Single Plot With Two Dimensionless Groups

New Dimensionless Parameters and a Power Law Correlation

Questions & Comments ?

New Dimensionless Parameters and a Power Law Correlation for Pressure Drop of Gas-Liquid Flows in Horizontal Pipelines

Al-Sarkhi Abdel

Abstract

New dimensionless parameters and a simplified correlation to predict pressure drop during the gas-liquid flow in horizontal pipes are proposed. The new equation fits the published data very well. The proposed power low equation can correlate the stratified-smooth, stratified-wavy, stratified-atomization, stratified-annular-transition and annular flow patterns. An approximate universal power law correlation is proposed. The proposed dimensionless formula can be used for the flow line design purposes and flow assurance predictions in pipelines.

Introduction

Gas-liquid two-phase flow in pipes is encountered frequently in nuclear, chemical and petroleum industries. Predictions of the pressure gradient and liquid holdup are very important for designing pipes, and for maintenance and operation of the downstream facilities. Compared to single phase fluid flow, two phase flow is more complex because more unknown parameters and different phase distributions or patterns are involved. An abundance of empirical correlations has been developed for predicting two phase flow steady pressure drops and liquid holdup (e.g. Chen et al. (1997); Hart et al. (1989); Chen and Spedding (1981); Hashizume (1985); Dukler at al. (1964); Muller-Steinhagen and Heck (1986)). Michael et al. (1997) used their experimental data to test the prediction of the pressure drop against different correlations from literature. It was concluded that several correlations were only successful in prediction pressure drop for certain flow pattern only and prediction of smooth stratified, slug, and bubble flow were unsuccessful.

All correlations in literature were based on using different plots or equations for different conditions (flow pattern, superficial velocities, pipe diameter, gas and liquid densities etc). Most of the correlations constructed with large number of constants and parameters which makes it inconvenient to be easily used. The simplest model found in literature is by Muller-Steinhagen and Heck, which is still more complicated than the present proposed model and has several restriction conditions which must be satisfied before it can be applied.

Several unsuccessful attempts have been made to find a universal correlation for pressure drop prediction similar to that in single phase flow of pressure drop or even to form a dimensionless group that better presenting the data without much of constrained conditions. Finding dimensionless parameters to simplify the correlations is extremely important. This paper presents a new correlation with two new dimensionless groups; the normalized pressure gradient and the ratio of modified liquid and gas Froude numbers. This dimensionless numbers can be obtained from the momentum equation of liquid and gas. The new correlation covers the stratified-smooth, stratified-wavy, stratified-atomization, stratified-annular-transition and annular flow patterns.

Theoretical Analysis

Stratified Flow

The liquid and gas momentum equations for a stratified horizontal flow that shown in Fig. 1 can be written respectively as;

$$-A_L\left(\frac{dP}{dx}\right)-\tau_{WL}S_L+\tau_iS_i=0 \qquad (1)$$

$$-A_G\left(\frac{dP}{dx}\right)-\tau_{WG}S_G-\tau_iS_i=0 \qquad (2)$$

Where (dP/dx) is the pressure gradient, A_L and A_G are the cross sectional area covered of liquid and gas respectively, τ_{WL} and τ_{WG} are the liquid and gas wall shear stresses, respectively, S_L and S_G are the wetted perimeter of liquid and gas, respectively, and τ_i and S_i are the interfacial shear stress and the interface distance between the two phases.

Assuming the gas and liquid pressure gradients are equal at a given pipe cross section, the following pressure gradient equation, Eq. 3, can be found by adding Eqs. 1 and 2.

$$\frac{dP}{dx} = \frac{-1}{A_L + A_G}\left[\tau_{WG}S_G + \tau_{WL}S_L\right]. \tag{3}$$

Liquid and gas shear stresses are expressed, respectively as,

$$\tau_{WL} = f_L \frac{\rho_L U_L^2}{2}, \tag{4}$$

$$\tau_{WG} = f_G \frac{\rho_G U_G^2}{2}. \tag{5}$$

Where f, ρ, U are the friction factor, density and velocity.

By multiplying with the pipe diameter, D, and dividing by the dynamic pressure of the liquid, $\rho_L U_L^2/2$, Eq. 3 can be simplified and rearranged as,

$$\frac{(dP/dx)D}{\frac{1}{2}\rho_L U_{SL}^2} = D\frac{-A_P}{A_L^2}\left\{S_L f_L + S_G f_G \frac{\rho_L}{\rho_G}\frac{U_G^2}{U_L^2}\right\}. \tag{6}$$

A dimensionless pressure drop parameter can be defined as,

$$P^* = \frac{D(dP/dx)}{\frac{1}{2}\rho_L U_{SL}^2}. \tag{7}$$

Where D is the pipe inner diameter, (dP/dx) is the pressure gradient, ρ_L is the density of the liquid and U_{SL} is the superficial liquid velocity and A_P is the pipe cross sectional area.

The other dimensionless parameter, X^*, is defined as the ratio of the Modified Froude number, Fr_L, based on the superficial liquid velocity to the Modified Froude number, Fr_G, based on the superficial gas velocity.

$$X^* = \frac{Fr_L}{Fr_G}. \tag{8}$$

The modified gas and liquid Froude numbers are respectively given with Eqs. 9 and 10.

$$Fr_G = \sqrt{\frac{\rho_G}{\rho_L - \rho_G}}\frac{U_{SG}}{\sqrt{Dg\cos\alpha}}. \tag{9}$$

$$Fr_L = \sqrt{\frac{\rho_L}{\rho_L - \rho_G}}\frac{U_{SL}}{\sqrt{Dg\cos\alpha}}. \tag{10}$$

Where g is the acceleration due to the gravity, and α is the angle of inclination of the pipe. The Froude number ratio can be rewritten using Eqs. 9 and 10 as follows:

$$X^* = \frac{\dot{m}_L}{\dot{m}_G}\sqrt{\frac{\rho_G}{\rho_L}}. \tag{11}$$

Where $\dot{m}_L$ and $\dot{m}_G$ are the liquid and gas mass flow rates, and ρ_L and ρ_G are the liquid and gas densities.

Using the parameter, X^*, defined above, Eq. (6) can be rewritten as:

$$P^* = -D\frac{A_P}{A_L^2}\left\{S_L f_L + S_G f_G \left(\frac{A_L}{A_G}\right)^2 X^{*-2}\right\}. \tag{12}$$

Furthermore, Eq. (12) can be simplified using the following dimensionless parameters for the length scale:

$$S_L^* = \frac{S_L}{D};\ S_G^* = \frac{S_G}{D};\ A_L^* = \frac{A_L}{D^2};\ A_G^* = \frac{A_G}{D^2} \tag{13}$$

Equation (12) can be written as

$$P^* = -\frac{\pi}{4}\left\{\frac{S_L^* f_L}{A_L^{*2}} + \frac{S_G^* f_G}{A_G^{*2}} X^{*-2}\right\}. \tag{14}$$

Thus, P^* is a function of X^* and other parameters (S_L, f_L, D, A_L, A_G, S_G) which can be expressed as unique functions of liquid holdup (H_L). This indicates that there is a unique relationship between P^*, X^* and H_L.

Annular Flow

Following the same analysis above, the liquid momentum equation, Eq. (1) can also be written for annular flow as,

$$\frac{(dP/dx)D}{\frac{1}{2}\rho_L U_{SL}^2} = D\left(\frac{A_P}{A_L}\right)^2 \times \left\{-\frac{S_L f_L}{A_L} + \frac{S_i f_i}{A_L}\frac{\rho_G}{\rho_L}\frac{(U_G - U_L)^2}{U_L^2}\right\} \quad (15)$$

Note that for an annular flow $U_L << U_G$, then last term in Eq. (15) can be approximated as $(U_G - U_L)^2 \approx U_G^2$, then, using the same dimensionless parameters defined above, Eq. (13) can be simplified as,

$$P^* = \left(\frac{\pi}{4}\right)^2 \frac{1}{A_L^*}\left\{-\frac{S_L^* f_L}{A_L^{*2}} + \frac{S_i^* f_i}{A_G^{*2}} X^{*-2}\right\}. \quad (16)$$

Here, again, P^* is a function of X^* and other parameters which can be expressed as unique functions of liquid holdup (H_L). This indicates that there is a unique relationship between and P^*, X^* and H_L.

Comparison with Experimental Data and Correlation Development

In general, P^*—X^* correlation tested against 1300 published experimental data points that covers the stratified-smooth, stratified-wavy, stratified-atomization, stratified-annular-transition and annular flow patterns, different inclination angle, various liquid and gas viscosities, pipeline diameter, pipe type and pressure, and showed very self-similar behavior. An example of how well the P^* and X^* can correlate a gas-liquid flows can be shown in Figs. 2A and 2B for the data of Chen et al. (1997).

Using the P^* as an ordinate and X^* as abscissa all the published pressure drop data (see Fig. 3) follow almost exactly a power law like formula for the value $X^* < 0.3$ (equivalent to liquid loadings less than 9750 $m^3/MMsm^3$, which can be written as,

$$P^* = A(X^*)^B. \quad (17)$$

Where A and B are correlation constants. The data start to deviate from the power law for the values of $X^* > 0.3$. In many cases the power law can be extended to a higher value of X^* than 0.3.

In Fig. 3, one large diameter high pressure data (in the froth/slug flow pattern) of Brill et al. in Prudhoe Bay field is also plotted and surprisingly showed good trend even it has value of $X^* > 0.3$ and a forth/slug flow pattern and the pipe is not horizontal. Figure 4 shows another example of a very good fit for a liquid at a different liquid viscosity. Figure 5 shows the inclination effect on the power law trend.

Table 1 shows a comparison of selected published data with the proposed power law. The first, second and third columns give the data source, pipe diameter, and pipe inclination angle information. The forth and fifth columns show the power law constants while the sixth column shows the R-squared value or the coefficient which reveals how closely the estimated values correspond to the experimental data points. Although Eqs. 14 and 16 are derived for a horizontal pipe, the comparison in Table 1 shows that the power law relation is still useful for inclined pipes as can be seen in Fig. 4.

Finally, an approximate universal power law correlation for the values of $X^*<0.5$ is proposed for horizontal pipes. The proposed correlation versus the published data for different pipe diameter, varies flow pattern, superficial gas and liquid velocities, gas and liquid densities, pipe type and pressure and liquid viscosities (from 0.78- 80 CP) is shown in Fig. 6. The best curve that fits the data can be written as,

$$P^* = 0.0895X^{*-1.8106}. \quad (18)$$

The R^2 value for the equation is 0.9815.

Concluding Remarks

The proposed power law formula fits very well all the published data for $X^* < 0.3$ which is encountered in the low-liquid loading studies. The equation start to deviate from the power low for values of $X^*>0.3$ but still can be extended to higher values of X^* as shown in Figs. 3 and 6. P^*—X^* power low equation can correlate the stratified-smooth stratified-wavy, stratified-atomization, stratified-annular-transition and annular flow patterns.

The formula is useful to predict the pressure drop for the design purposes by knowing the mass flow rates of gas and liquid or can be used to predict the amount of liquid presented in a pipeline by knowing the pressure drop. The simplicity in presenting and correlating many of the data points in a single plot with two dimensionless groups for variety of variables is another big advantage.

Nomenclature

A, B	Constants in the power law equation
A_G	Cross sectional area of a pipe occupied with gas
A_L	Cross sectional area of a pipe occupied with liquid
D	Pipe diameter
H_L	Liquid holdup
U_{SL}	Superficial liquid velocity
$\frac{dP}{dx}$	Pressure gradient
$\dot{m}_L$	Liquid mass flow rate
$\dot{m}_G$	Gas mass flow rate
S_L	Liquid wetted pipe perimeter
S_G	Gas wetted pipe perimeter
S_i	Interface length between gas and liquid
τ_{WL}	Liquid wall shear stress
τ_{WG}	Gas wall shear stress
τ_i	Interfacial shear stress
ρ_L	Liquid density
ρ_G	Gas density
X^*	Modified Froude Number Ratio
P^*	Normalized Pressure

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Table* 1: Evaluation of the power law equation using published data

Data Source	Pipe-ID (m)	Angle	A	B	R^2
Fan (2005)	0.1524	0	0.0576	-1.7838	0.9988
Fan (2005)	0.1524	2	0.1115	-1.6504	0.9897
Fan (2005)	0.1524	-2	0.038	-1.8761	0.9994
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Fan (2005)	0.0501	2	0.0884	-1.7625	0.9921
Fan (2005)	0.0501	-2	0.0642	-1.8169	0.9762*
Meng et. al (2001)	0.0501	0	0.00009	-1.8565	0.9949
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Mukherjee (1979)	0.0381	0	0.0366	-1.964	0.9788
Cheremisinoff (1977)	0.063	0	0.0964	-1.7666	0.9740
Beggs & Brill (1973)	0.025	0	0.678	-0.9639	0.9393*
Beggs & Brill (1973)	0.025	10	0.9017	-0.8887	0.9017*
Beggs & Brill (1973)	0.025	-10	0.5257	-0.9614	0.9199*
Beggs & Brill (1973)	0.0381	0	0.4799	-1.1338	0.9697
Beggs & Brill (1973)	0.0381	10	1.0769	-1.1085	0.9270*
Beggs & Brill (1973)	0.0381	-10	0.3224	-1.2549	0.9740

*Note: Only data with X^*>0.3 has the values of R^2<0.98

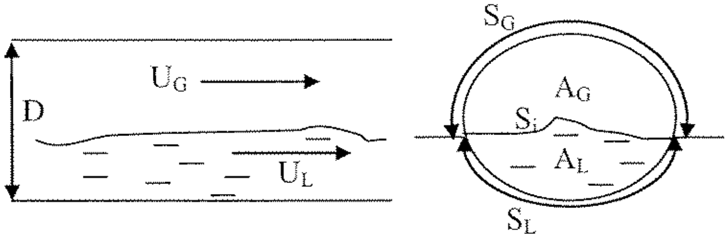

Figure 1: Stratified flow configuration and parameters

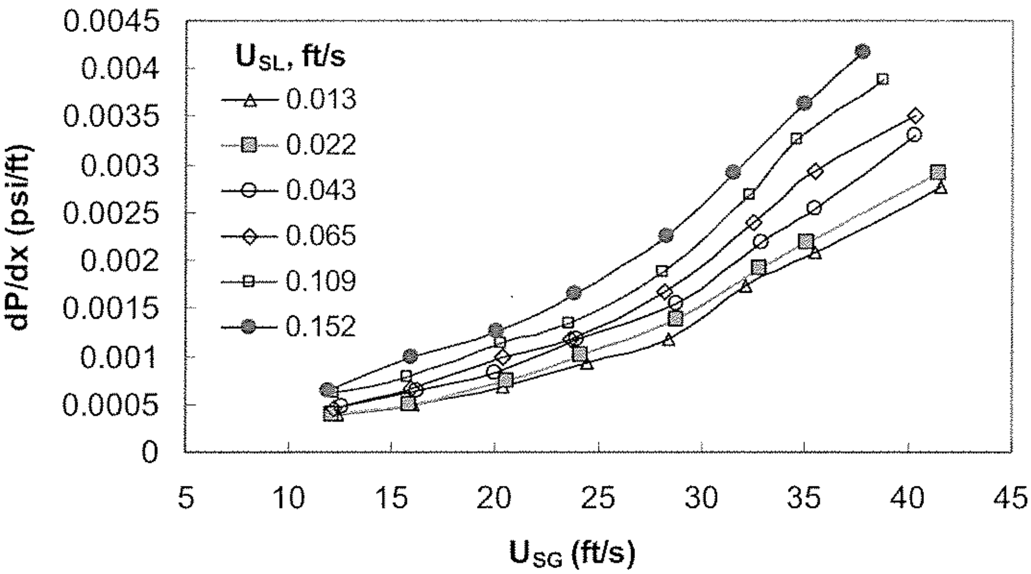

Figure 2A: Chen at al. (1997) data for air and kerosene in 3.068 inch pipeline

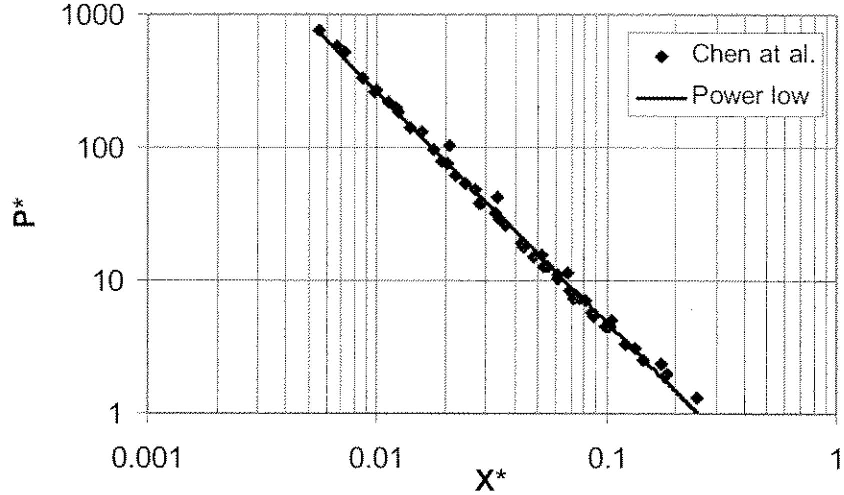

Figure 2B: Chen at al. (1997) data for air and kerosene in 3.068 inch pipeline

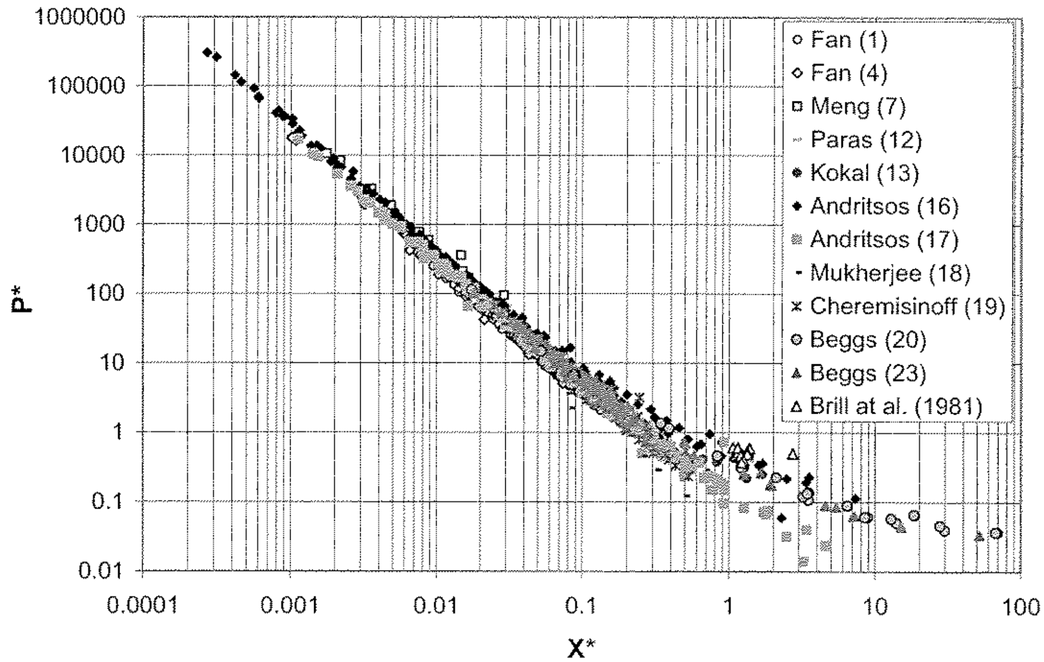

Figure 3: Power law evaluation using published data for gas-liquid in horizontal pipelines

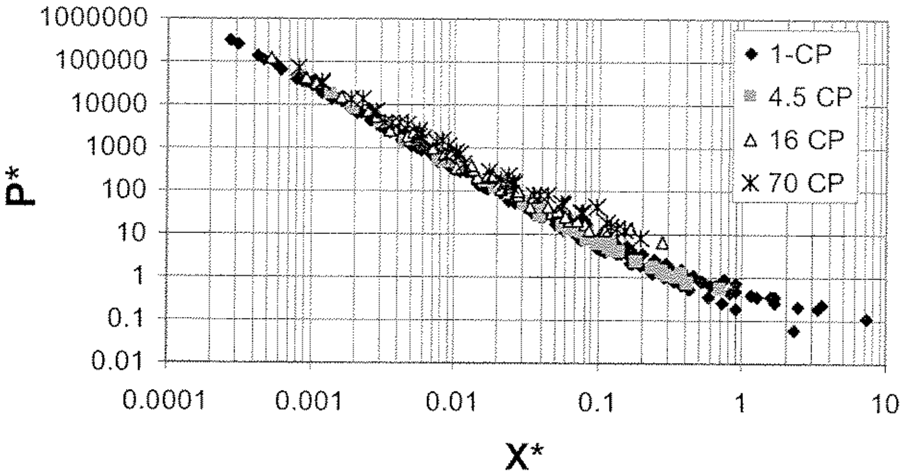

Figure 4: Andritsos (1986) data of air and Glycerin solution for different viscosity in 0.0254-m pipeline

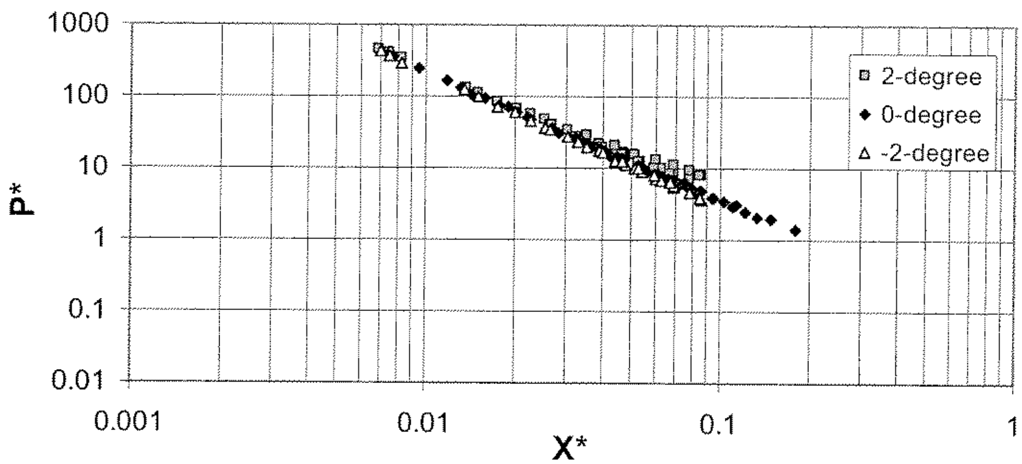

Figure 5: Fan (2005) data for air and water in 0.1524 m pipeline at different inclinations

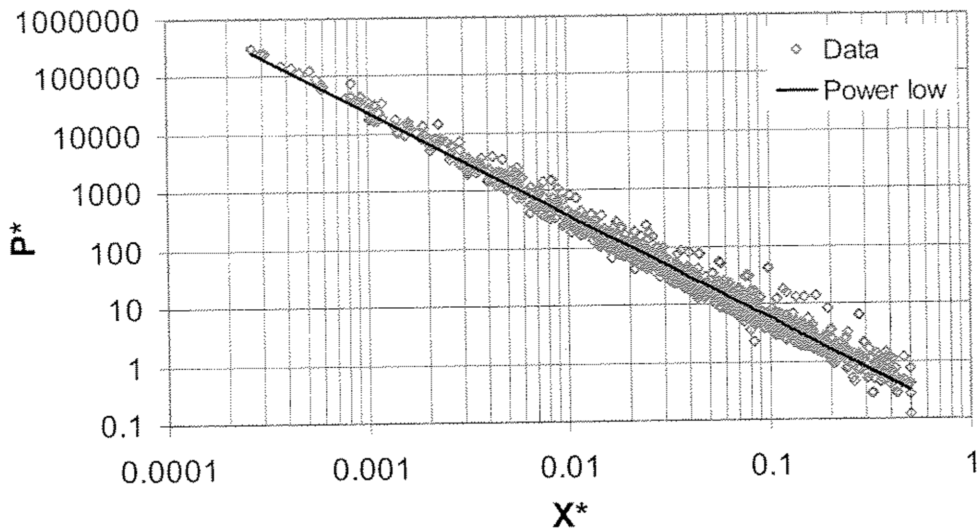

Figure 6: An approximate universal power law equation for gas-liquid flows in horizontal pipes

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, November 6, 2007

Outline

- Significance
- Objectives
- Literature Review
- 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 Oils in Horizontal and Near-Horizontal Pipes
- Validate Proposed Models with Experimental Results

Literature Review

- Literature Review Covers Slug Flow and Effects of High Oil Viscosity on Multiphase Flow Studies
- Literature Review was Presented at TUFFP Advisory Board Meeting Brochure of April 21, 2007

Experimental Facility

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

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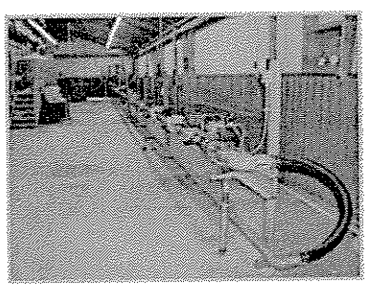
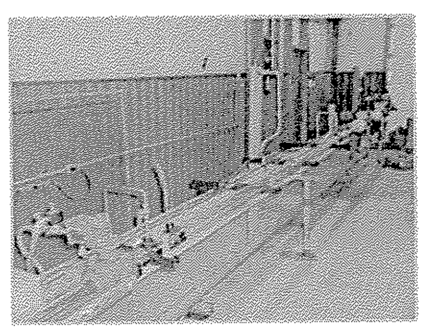
Experimental Facility ...



2-in ID High Viscosity Indoor Facility

Test Section



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Facility Modifications

- Change Oil Tank (1500 gallon)
- Connect Cooling System of Single Phase Deposition Facility to High Viscosity Facility
- Install Visualization Box on Test Section
- Install New Capacitance Sensors and Laser Sensors on Test Section

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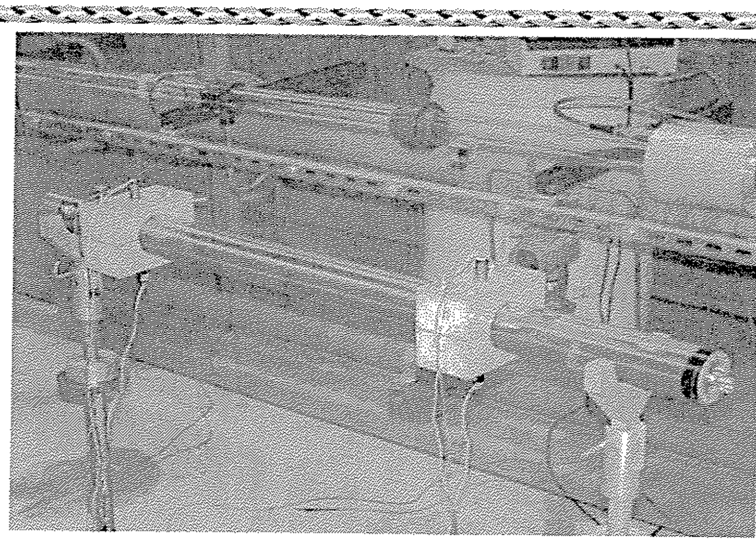
Laser Sensors



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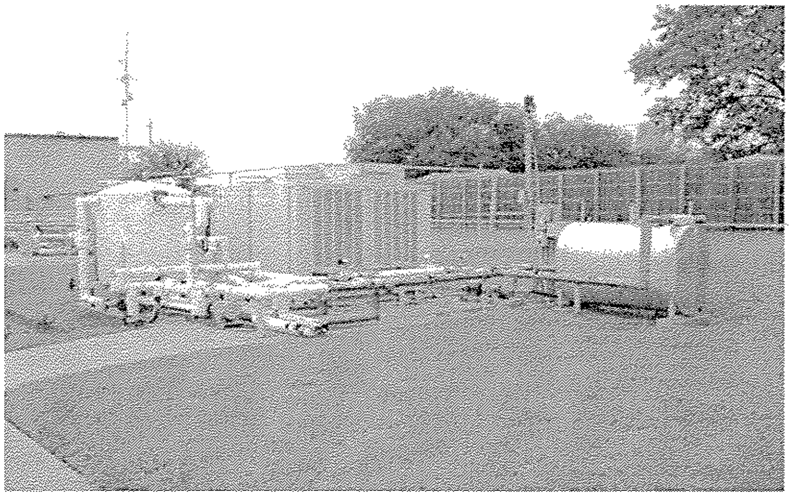
Cooling System



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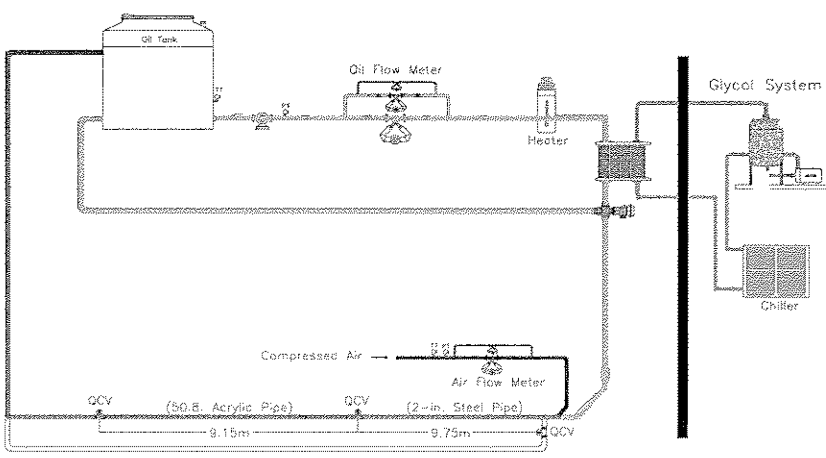
Experimental Facility ...



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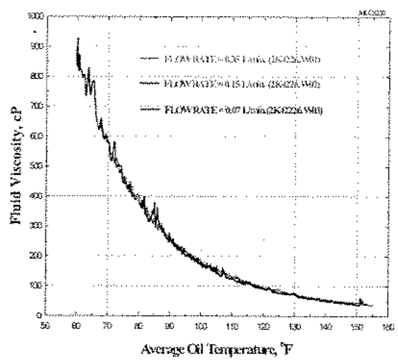
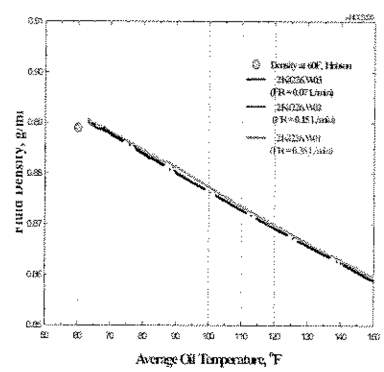
Test Fluid

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

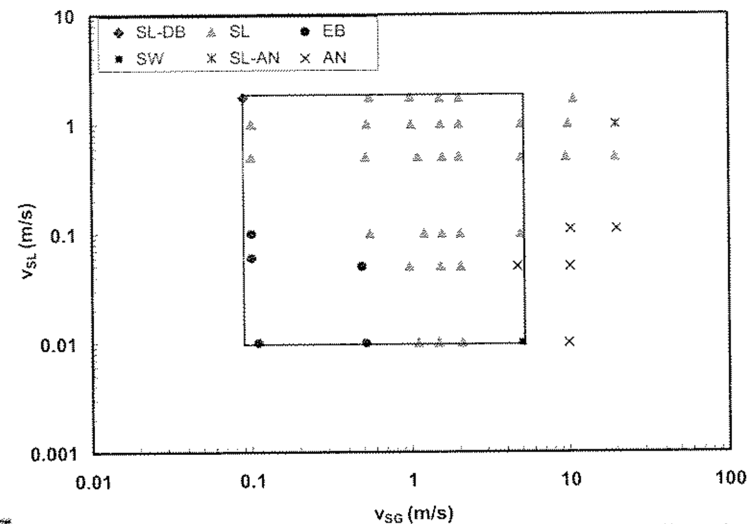




Testing Range

- 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 ...



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Instrumentation

- Pressure and Differential Pressure Transducers
- High Speed Video System
- Laser Sensors
- Quick Closing Valves
- Capacitance Sensors

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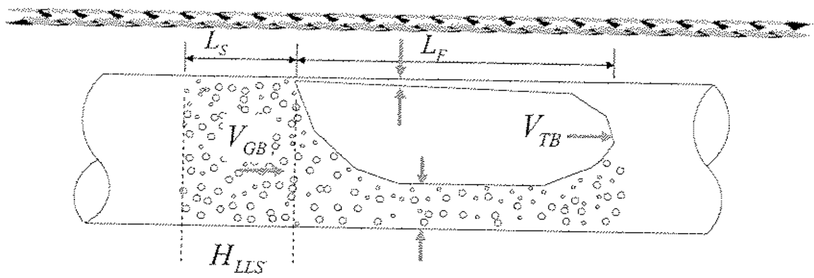
Modeling Study



- Translational Velocity
- Slug Holdup and Bubble Velocity in Liquid Slug Region
- Slug Length and Frequency
- Film Void Fraction
- Falling Film in Bubble Region
  - Thickness
  - Velocity

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Translational Velocity

- **Nicklin et al. (1962) proposed**

$$v_T = C_S v_s + v_D$$

- **Wallis (1969), Dukler and Hubbard (1975)**
  - No Drift Velocity Considered for Horizontal Case Since Gravity Can not Act in Horizontal Direction
- **Zukoski (1966) and Benjamin (1968)**
  - Drift Velocity Exists for Horizontal Case and Value of Drift Velocity Can Exceed Vertical Case Value

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Drift Velocity

- 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

Drift Velocity ...

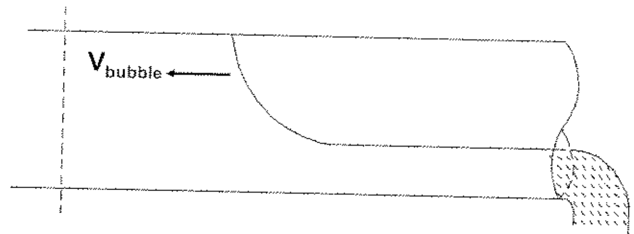
- Bendiksen (1984) Proposed for All Inclination Angles

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

- No Published Studies Addressing Effect of Viscosity on Drift Velocity Found Other than Zukoski's Study
- Drift Velocity is Expected to Be Affected by High Oil Viscosity

Drift Velocity ...

- Based on Benjamin's Theoretical Study Related to Translational Velocity, Existing Facility Modified



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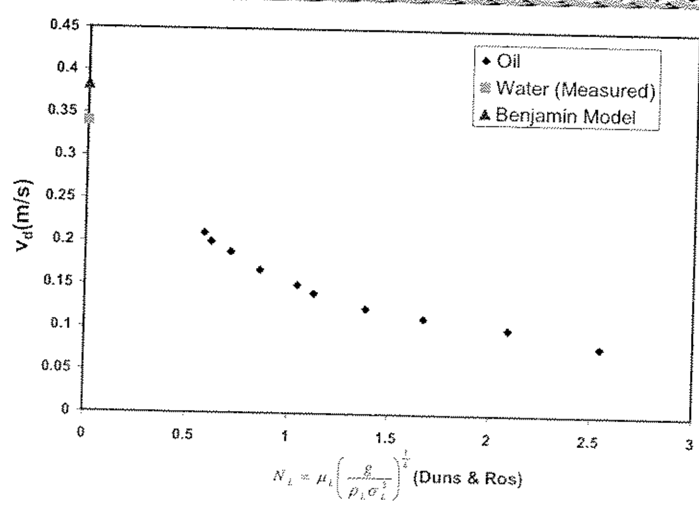
Drift Velocity ...



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Drift Velocity …

- Wallis (1969) Proposed

Froude Number

$$Fr_D = \frac{v_D}{(gD)^{0.5}}\sqrt{\frac{\rho_L}{(\rho_L-\rho_G)}}$$

Viscosity Number

$$N_\mu = \frac{v_D \mu_L}{gD^2(\rho_L-\rho_G)}$$

Eötvös or Bond Number

$$N_{E\ddot{o}} = \frac{\sigma}{gD^2(\rho_L-\rho_G)}$$

Archimedes Number

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

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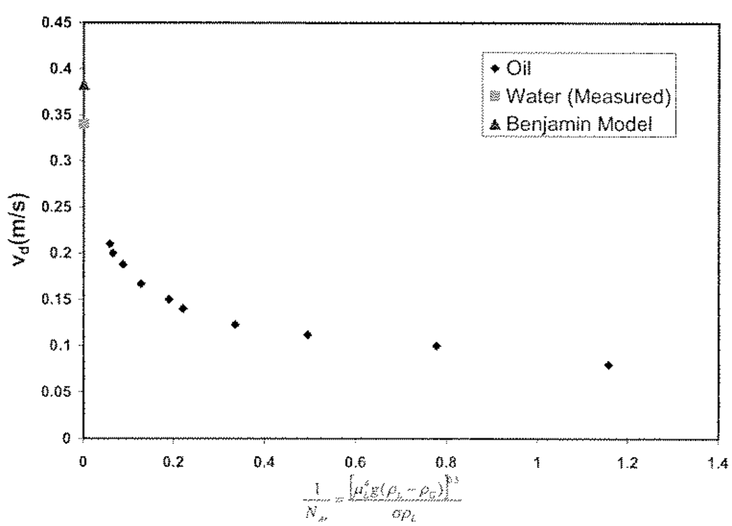
Drift Velocity …



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Drift Velocity ...

Experimental Study Program

Single Large Bubble in Stagnant Liquid
(Liquid Drainage)

↓

Single Large Bubble in Flowing Liquid

↓

Continuous Slug Flow

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Future Work

- Complete Drift Velocity Study
- Complete Facility Modifications
- Shake Down Tests of Facility
- Prepare Testing Program
- Conduct Experiments
- Develop Closure Models

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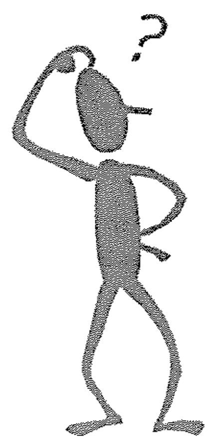
Project Schedule

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

Questions & Comments



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	February 2008
Preliminary Testing	March 2008
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,
- 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.

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 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 sufficient for high viscosity oils. It was found that increasing oil viscosity had a significant effect on flow behaviors. Mostly, intermittent flow (slug and elongated bubble) was observed in his study. Based on his results, this study is focused on slug flow region for high viscosity oil. The knowledge of the slug flow characteristics is crucial to design pipelines and process equipments. In order to improve the accuracy of slug characteristics for high viscosity oils, accurate closure models for slug flow are needed.

The TUFFP High Viscosity Facility (2-in. ID) has been modified. Drift velocity experiments were conducted at different temperatures for horizontal pipe.

Air-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.

Literature Review

The literature review addressing slug flow and high viscosity oil in multiphase flow was reported in the TUFFP Advisory Board Meeting brochure of April 24, 2007. It will be a continuing effort until the modeling studies are completed.

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. The 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. The metering section, test section, heating and cooling systems are the major components of the facility as shown in Fig. 1.

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. The DP3 which covers 3.05-m (10-ft) of the transparent pipe is mainly used for high flow rates. The DP4 which covers 6.55-m (20-ft) of the transparent pipe is used for low flow rates. The test section is instrumented to permit continuous monitoring of liquid flow rate, gas flow rate, temperature, pressure, differential pressure, and spatial distribution of the phases. TUFFP high speed video system will be used to identify the flow patterns. New visualization box is installed on the acrylic pipe to observe and record flow patterns in details.

Separation of oil and air is the biggest challenge of conducting high viscosity oil tests. The existing oil tank capacity is 1200 gallon and it is open to the atmosphere. For high flow rates, air bubbles can be observed in the viscous oil. Several separation techniques are investigated to solve this problem. As a solution, replacing the existing tank with a new plastic one (1500 gal.) is decided. The tank has an additional internal configuration located at returning pipe. It will be long enough to reach to oil surface. This modification will solve oil splashing.

The cooling system is shared with small scale facility. The 12-ton chiller is not enough when two facilities run at the same time. After several options are investigated, it is decided to connect the cooling system of single-phase deposition facility to high viscosity test facility. The cooling system of single phase facility has 60-ton chiller capacity. This modification will give better opportunity to control temperature system precisely during tests. Also, a heat exchanger is needed to trim (add or remove) temperature per pass for high viscosity oil experiments. Therefore, double tube heat exchanger will be added to the facility. A modified schematic of the facility is given in Fig. 1.

New instruments have been discussed based on the objectives of the study. Capacitance sensors were used to measure the liquid holdup and slug characteristics. Their performances were not sufficient. A new capacitance sensor is designed and will be installed to the facility. Laser beams and sensors are installed on the test section. Their calibrations are completed. They are being used for the measurement of drift velocity now. They will be also conducted to measure slug characteristics. A high speed video camera will be used to capture details of slug flow. Search for new instruments will be a continuing effort until facility modifications are completed.

Test Fluid

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

- 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 are shown in Figs. 2 and 3, respectively.

Experimental Range

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

It is known that significant amount of air bubbles can be entrained in liquid with increasing gas flow rate. Diameter of air bubbles gets smaller with higher gas flow rates. The color of oil changes completely. The new mixture can be accepted as foam. Foam is a big challenge for separation. Therefore, a critical air velocity has to be known to prevent foam formation in the experimental study. A study is conducted by using experimental observations to determine critical gas velocity that gives transition from air bubbles to air particles in liquid. All video recordings are investigated carefully. It is found that the critical gas velocity should be 5 m/s. If the gas velocity is higher than this velocity, foaming will be observed.

Figure 4 shows the experimental observations of flow patterns at oil viscosity of 0.181 Pa·s. The marked area in the flow pattern is the velocity limits for future high oil viscosity experiments.

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, film void fraction, falling film in bubble region including thickness and velocity.

Translational Velocity

Translational velocity is composed as superposition of the velocity of the bubble velocity in stagnant liquid, i.e. the drift velocity v_d, and a contribution of the mixture velocity, v_s.

Nicklin et al. (1962) proposed an equation for translational velocity as,

$$v_t = C_s v_s + v_d . \quad (1)$$

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.

Wallis (1969), Dukler and Hubbard (1975) claimed that there is no drift velocity for horizontal case since gravity can not act in horizontal direction. However, Zukoski (1966) and Benjamin (1968) proved that drift velocity exists for horizontal case and the value of drift value can exceed the vertical case value. The drift velocity results from hydrostatic pressure difference between top and bottom of the bubble nose.

For the drift velocity, Benjamin (1968) proposed the following relationship for horizontal pipes,

$$v_d = 0.54\sqrt{gD} \quad (2)$$

Benjamin (1968) calculated the value of 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 for horizontal pipe. Bendiksen (1984) and Zukoski (1966) supported the study of Benjamin (1968) experimentally.

Bendiksen (1984) 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,

$$v_d = v_d^h \cos\beta + v_d^v \sin\beta , \quad (3)$$

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

Zukoski (1966) experimentally investigated the effects of the 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>200. ($Re=V_d \rho D/\mu$)

No published studies addressing the effect of viscosity on the drift velocity was found other than Zukoski's study. However, the drift velocity is expected to be affected with high viscosity.

At this point, the aim of the study is to investigate the effect of high oil viscosity on drift velocity of single elongated bubbles in stagnant liquid. Based on future experimental results, modification of existing models or new closure model on drift velocity for high viscosity oils will be necessary.

The existing facility was modified during summer to conduct bubble penetration or liquid drainage experiments. Oil is captured by quick closing valves at desired temperature. The outlet of the pipe can be opened to atmosphere manually. When oil is drained from horizontal pipe, the velocity of the penetration of air bubble was measured by laser beams and sensors. The experiments are performed at temperatures between 70°F and 112°F. The oil viscosities corresponding to the above temperatures are 124 and 587 cP, respectively. Moreover, one experiment is conducted for water.

Figure 5 presents the measured drift velocities at different oil viscosities and surface tensions. Dimensionless liquid viscosity number, N_L is applied for the graph to show viscosity and surface tension parameters in one equation. Duns & Ros (1963) proposed liquid viscosity number N_L, as

$$N_L = \mu_L \left(\frac{g}{\rho_L \sigma_L^3} \right)^{\frac{1}{4}}. \qquad (4)$$

It is seen that the effect of high viscosity played an important role on the drift velocity. The drift velocity decreases with the increase of oil viscosity and with the decrease of oil surface tension.

Wallis (1969) completed an extensive dimensionless analysis for inertia, viscous and surface tension forces.

The dimensionless Froude number for the inertia forces is defined as,

$$Fr_D = \frac{v_D}{(gD)^{0.5}} \sqrt{\frac{\rho_L}{(\rho_L - \rho_G)}}. \qquad (5)$$

The dimensionless viscosity number for the viscous forces is defined as,

$$N_\mu = \frac{v_D \mu_L}{gD^2(\rho_L - \rho_G)}. \qquad (6)$$

The Eötvös or Bond number for the surface tension forces is defined as,

$$N_{Eö} = \frac{\sigma}{gD^2(\rho_L - \rho_G)}. \qquad (7)$$

The dimensionless inverse viscosity can be obtained by combining the first two dimensionless groups,

$$N_{IV} = \frac{\left[gD^3 \rho_L (\rho_L - \rho_G)\right]^{0.5}}{\mu_L}. \qquad (8)$$

Combining Eqs. (5), (6) and (7), the Archimedes dimensionless number is obtained. It depends on only fluid properties and gravitational acceleration and can be written as follows

$$N_{Ar} = \frac{\sigma \rho_L}{\left[\mu_L^4 g(\rho_L - \rho_G)\right]^{0.5}}. \qquad (9)$$

Figure 6 shows the experimental results for drift velocity vs. Archimedes dimensionless number. This dimensionless number is chosen to observe the effect of fluid properties. The drift velocity decreases with the decrease of Archimedes dimensionless number and with the increase of oil viscosity.

The experimental results show that viscosity parameter must be added to drift velocity equation for horizontal pipe. New model on drift velocity for high viscosity oils is being developed.

Future Studies

The main tasks for the future are:

- Complete the facility modifications
- Shake down tests of the facility.
- Prepare the testing program.
- Conduct experiments.
- Develop the closure models.

References

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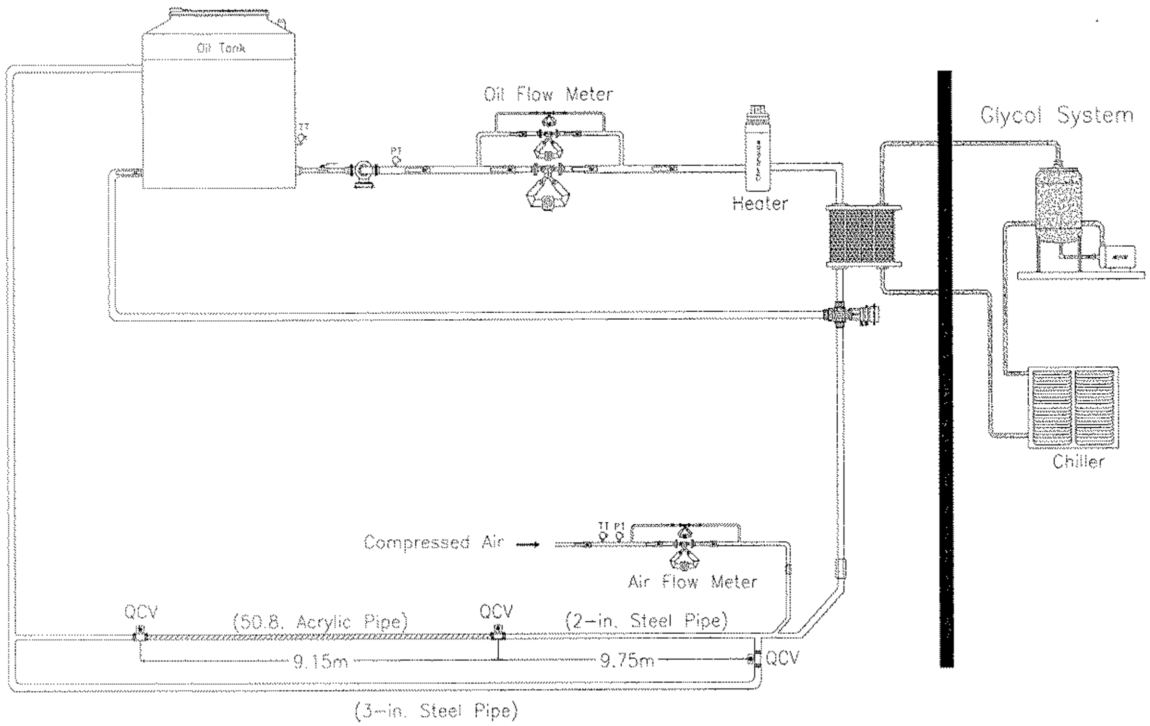


Figure 1 - Schematic of Test Facility

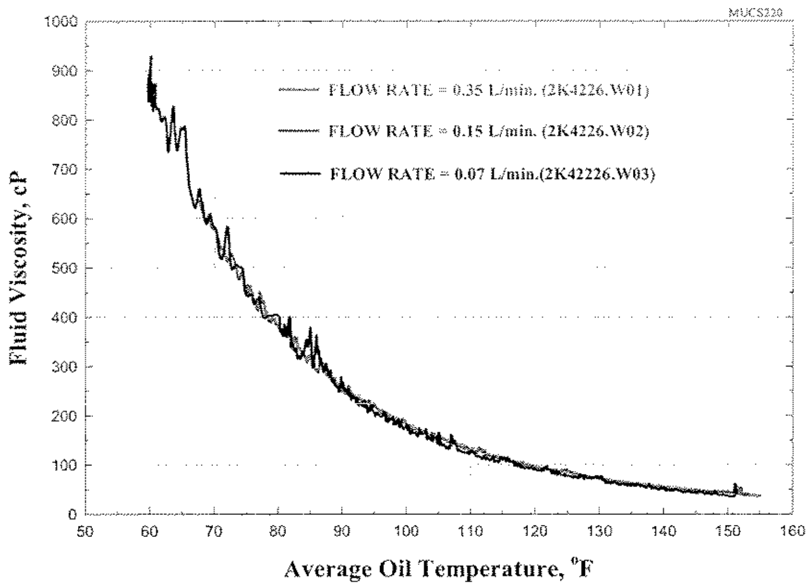


Figure 2 - Viscosity vs. Temperature for Citgo Sentry 220 Oil

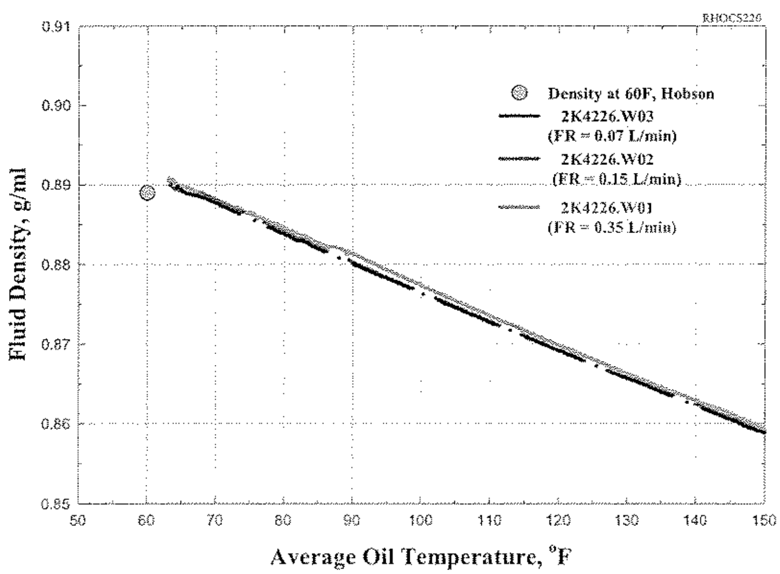


Figure 3 - Oil Density vs. Temperature for Citgo Sentry 220 Oil

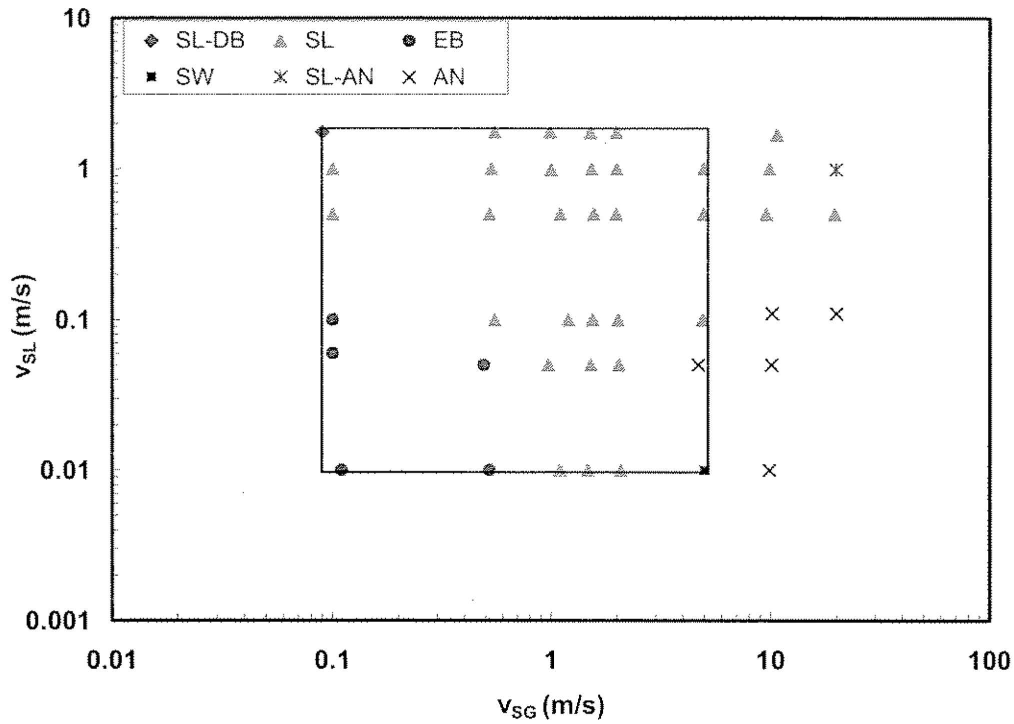


Figure 4 - Experimental Observation of Flow Patterns (0.181 Pa·s)

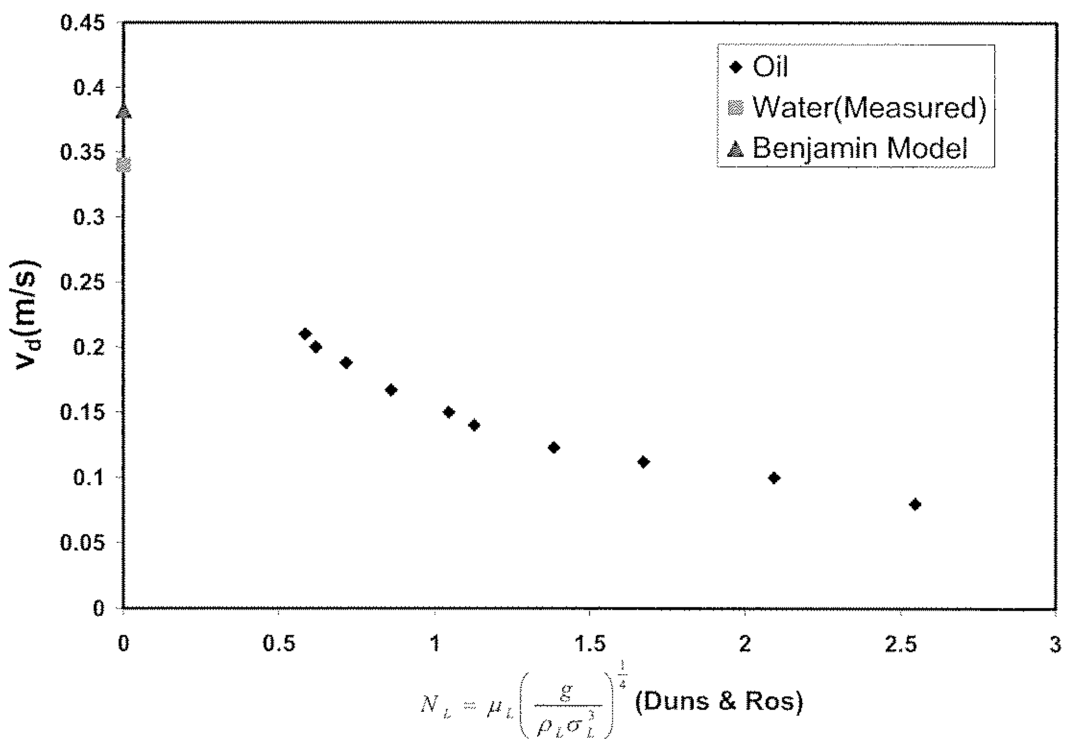
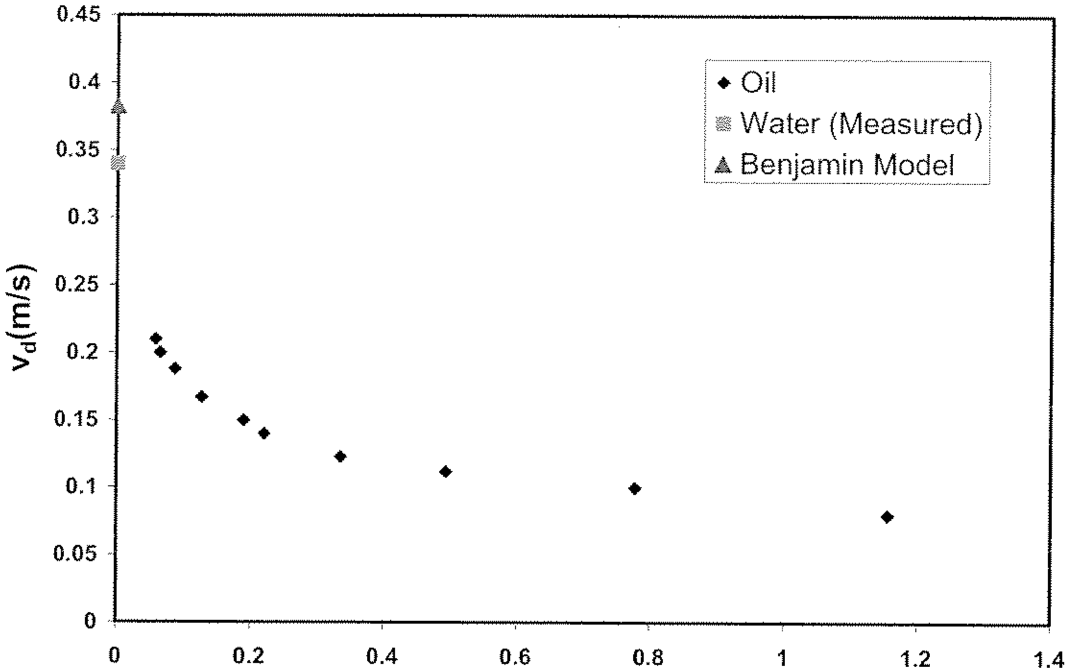


Figure 5 - Experimental Observation of Drift Velocity at Different Viscosities



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

Figure 6 - Experimental Observation of Drift Velocity at Different Viscosities

Fluid Flow Projects

Gas-Oil-Water Flow in Hilly-Terrain Pipelines

Gizem Ersoy Gokcal

Advisory Board Meeting, November 6, 2007

Outline

- Objectives
- Introduction
- Significance
- Three-Phase Flow Effects
- Literature Review
- Experimental Facility
- Project Schedule

Objectives

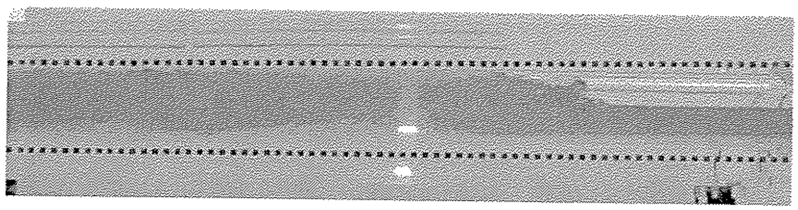
- Investigate Three-Phase Flow of Gas-Oil-Water in Hilly-Terrain Pipelines
- Develop Mechanistic Models and Closure Relationships Based on Theoretical Analysis and Experimental Results for Three-Phase Slug Flow Characteristics in Hilly-Terrain Pipelines

Introduction

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

Introduction ...

- Stratified Liquids



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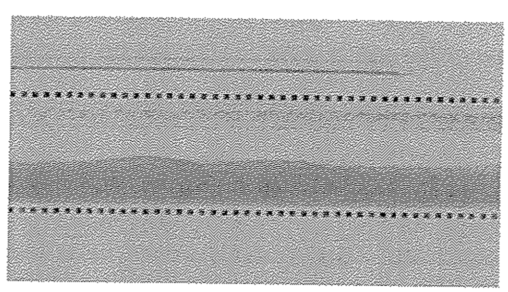
Introduction ...

- Oil Continuous



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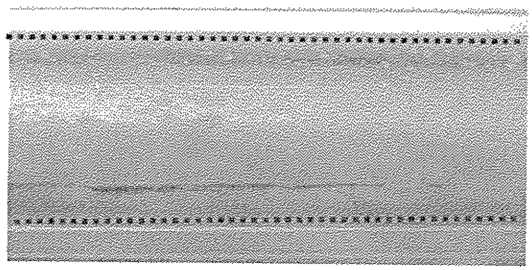
Introduction ...

- Water Continuous



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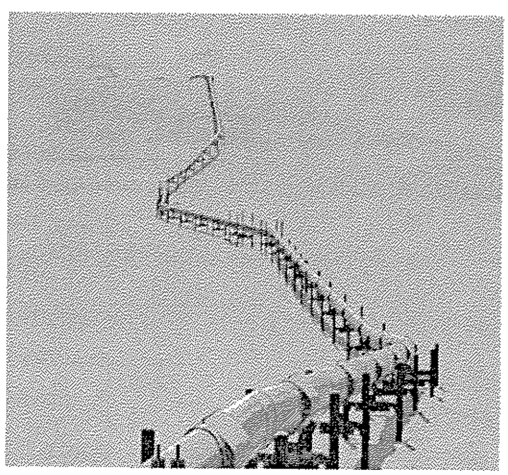
Introduction ...



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

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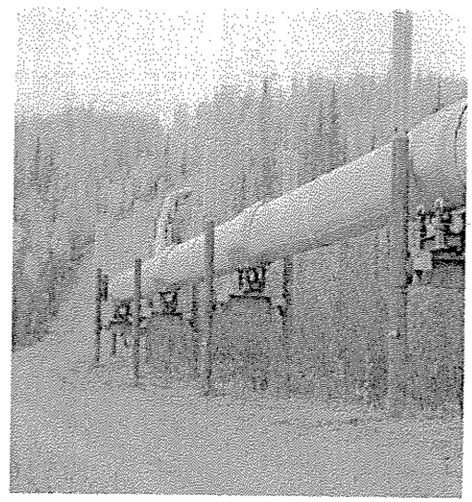
Introduction ...

- Flow May Exhibit Different Behavior



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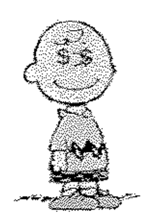
Significance

Hilly-Terrain Pipelines Cause

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



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Significance ...

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

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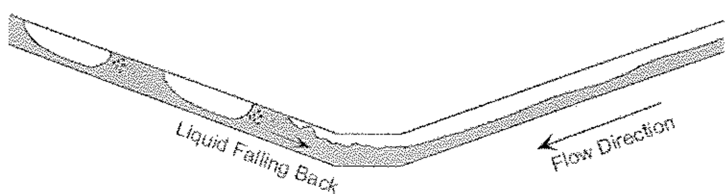
Three-Phase Flow Effects

- Hydrodynamics
  - Case-1



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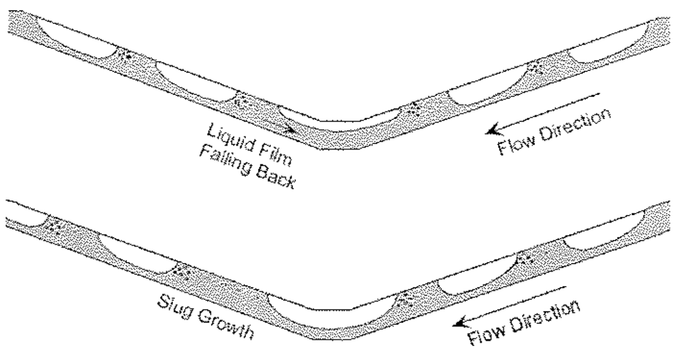
Three-Phase Flow Effects ...

- Hydrodynamics
  - Case-2



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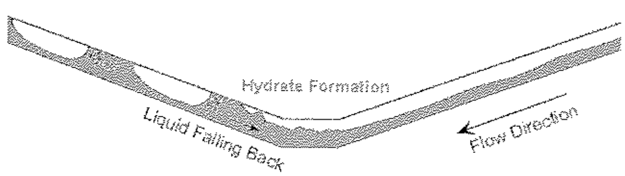
Three-Phase Flow Effects ...

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



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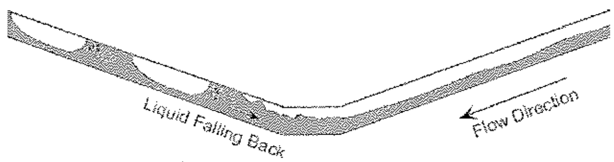
Three-Phase Flow Effects ...

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



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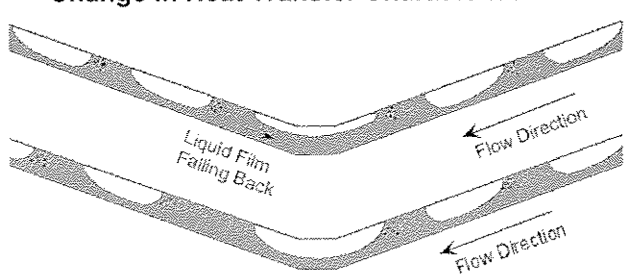
Three-Phase Flow Effects ...

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



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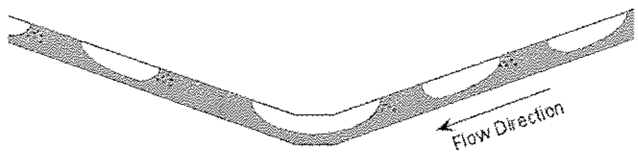
Three-Phase Flow Effects ...

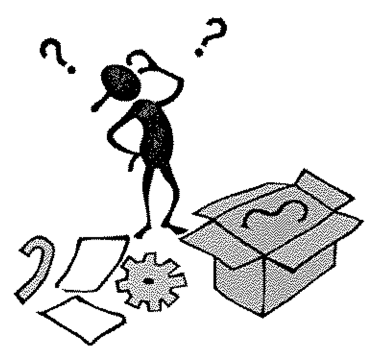
- Flow Assurance:
  - Corrosion
    - Changes in Slug Length and Frequency
    - Water Wet or Oil Wet Pipe?
    - Accumulation of Water at Low Spots



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

Literature Review

- Literature from Hilly-Terrain Studies and Three-Phase Flow are Searched
- Detailed Literature Review was Presented at ABM in April 2007
- No Studies Addressing Three-Phase Flow in Hilly-Terrain Pipelines Could Be Found



Experimental Facility

- Hilly-Terrain Facility
  - Existing Test Facility:
    - 420-m (1378-ft) Long
    - Parallel 50.8-mm (2-in.) and 76.2-mm (3-in.) Diameter Pipes
    - Single Hilly-Terrain Unit of 70-ft Uphill and 70-ft Downhill Sections
    - ±1°, ±2° of Inclination Angles

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Experimental Facility ...

- Modified Test Facility:
  - 76.2-mm (3-in.) Diameter Pipeline
  - Addition of:
    - Water Tank
    - New Separator
    - New Oil and Water Pumps from Seepex
    - Hilly-Terrain Unit & Measurement Stations
    - Data Acquisition System
    - Spill Prevention System

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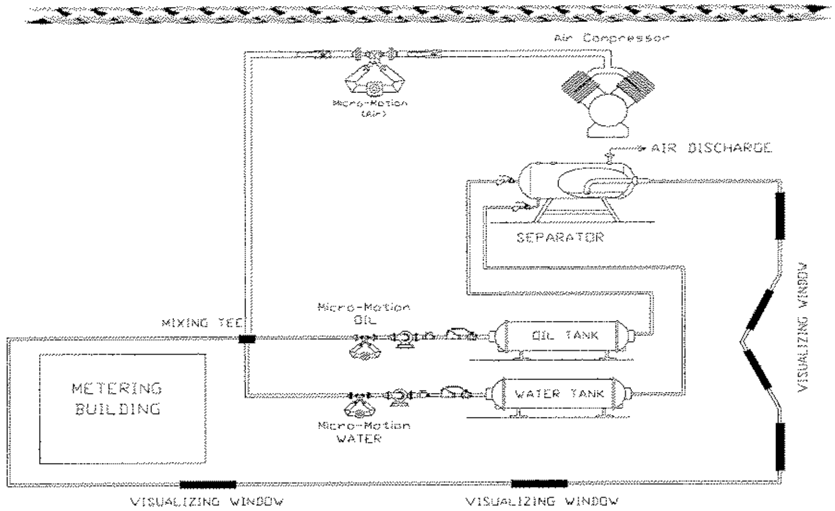
Experimental Facility ...



Experimental Facility ...

- Preliminary Study for Facility Limits
  - Run Simulations with TUFFP Unified Three-Phase Flow Program
  - Observed Slug Flow as Dominant Flow Pattern
  - Determined Hilly Terrain Facility Limits
    - $v_{SG} = 5 m/s$, $v_{SW} = 0.61 m/s$, $v_{SO} = 0.61 m/s$
    - $\Delta P_{max} = 570385$ Pa ($\approx$83psi)

Experimental Facility ...

- Spill Prevention System:
  - Welding of Steel Pipes
  - Usage of Expandable Joints to Connect Steel Pipes and Acrylic Pipes
  - Installation of Emergency Shutdowns and Security Cameras
  - Installation of PVC Pipes that will Surround Acrylic Pipes in Case of any Rupture

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Experimental Facility ...

- Spill Prevention System:
  - Usage of Plastic Curtains as Liquid Barriers at Visualization Stations in Case of Splashes of Liquid
  - Addition of Bypass Lines to Facility in Parallel to Visualization Stations
  - Containment Berms under Visualization Sections to Contain Spillage

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Experimental Facility …

- Gas-Oil-Water Test Facility:
  - Preliminary Analysis of Inclined Three-Phase Flow Patterns and Characteristics
    - Understanding of Steady Inclined Three-Phase Flow
    - Will Be Used for TUFFP Three-Phase Flow Studies
  - Application of Laser Beams and Sensors

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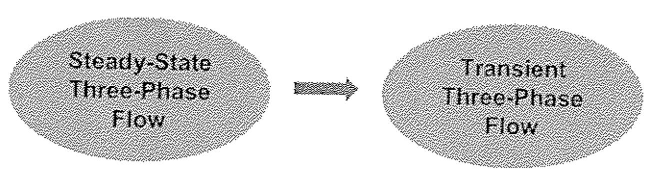
Experimental Facility …

- Gas-Oil-Water Test Facility:
  - Previously Run By Atmaca (2007)
  - Facility in Running Condition



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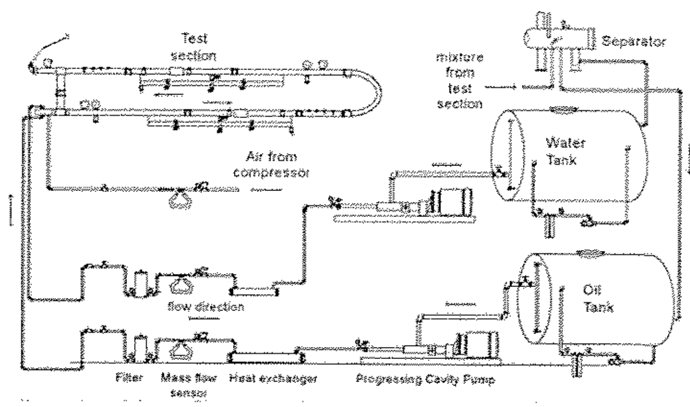
Experimental Facility …



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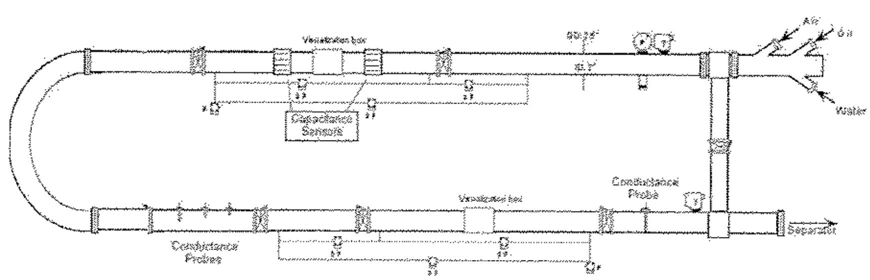
Experimental Facility …



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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)

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Instrumentation

- Capacitance Sensors
  - Slug Characteristics
- Conductance Probes
  - Phase Determination at a Point/Line
- Pressure & Differential Pressure Transducers
  - Pressure Drop
  - Identification of Flow Patterns

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Instrumentation ...

- Laser Sensors & Quick Closing Valves
  - Slug Flow Characteristics
  - Gas, Oil, Water Holdups
- High Speed Camera
  - Identification of Flow Patterns
  - Droplet Size Distribution
  - Slug Characteristics

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Project Schedule

Facility Modifications	March 2008
Preliminary Testing	May 2008
Testing	November 2008
Model Development	January 2009
Model Validation	February 2009
Final Report	May 2009

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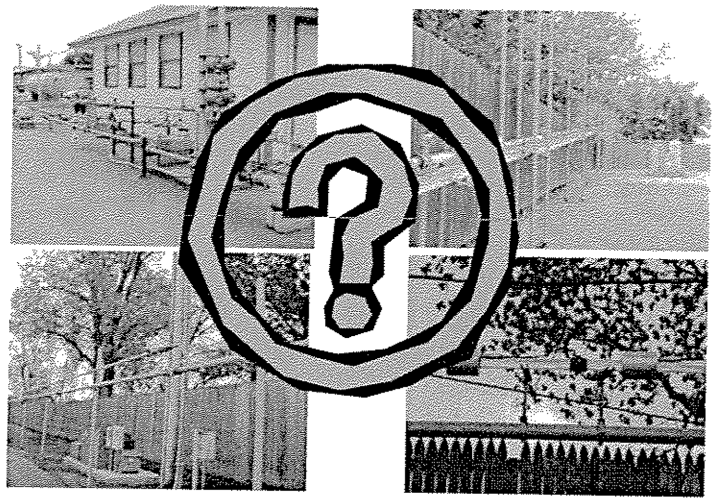
Questions & Comments



Fluid Flow Projects

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Multiphase Flow in Hilly-Terrain Pipelines

Gizem Ersoy Gokcal

PROJECTED COMPLETION DATES:

Literature Review	Completed
Facility Modifications	March 2008
Preliminary Testing	May 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 thoroughly investigate and compare existing models and develop predictive models and closure relationships for three-phase flow in hilly-terrain pipelines. These will require both experimental and theoretical study.

Significance and Literature Review

A hilly-terrain pipeline is considered as 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 petroleum industry, slug flow is the most complex and dominant flow pattern in horizontal and near horizontal pipe flow. 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 the flow assurance problems such as hydrates, emulsions and paraffin deposition. Corrosion and erosion depend also 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. It is also found that slug flow is the dominant flow regime in three-phase pipe flow. This strengthens the significance of slug flow studies for hilly-terrain configurations.

In the literature, early studies on hilly-terrain pipelines begin with Beggs and Brill (1973). They developed correlations that can be applied to design pipelines for hilly-terrain and tubing strings for inclined wells.

Throughout the years more research has been done on slug flow. Taitel and Barnea (1990), proposed a steady-state slug flow model. However, the model does not consider any changes in slug flow characteristics nor the slug growth and slug decay when the pipe inclination angle changes.

Scott (1987) studied slug growth in long large-diameter pipelines operating near stratified-slug transition boundary in the Prudhoe Bay field in Alaska. It was suggested that the interaction between the slug and the wave in the preceding film is the reason for the slug growth.

Scott and Kouba (1990) studied the changes in slug flow characteristics in hilly-terrain pipelines. They assumed no change in liquid holdup in the slug and an equilibrium film thickness. They did not consider slug initiation or dissipation in their model for the change in slug length.

The Tulsa University Fluid Flow Projects (TUFFP) has been involved in hilly-terrain flow research since the early 1970s. Sarica (1990) improved Taitel et al. (1990) by performing a more thorough analysis on severe slugging in a pipeline-riser system and extend his analysis to hilly-terrain pipelines. Zheng (1991) proposed simple slug tracking model that follows the behavior of all individual slugs for a single hilly-terrain unit. Marcano (1996) developed correlations for slug liquid holdup, film liquid holdup, slug translational velocity, slug frequency and slug lengths.

There have been slug-tracking models developed by Nydal and Banerjee (1996) and Greiner et al. (1997), Taitel and Barnea (1999). However, these models require additional information such as slug initiation, initial slug frequency, slug length distribution and translational velocity.

In a recent study by Al-Safran et al. (2003), a Log-Normal probability model was found to be the appropriate model for slug length distribution at the hilly-terrain entrance and lower dip. It is also shown that the probabilistic/mechanistic models are capable of reproducing the experimental results with a satisfactory match.

Zhang et al. (2000) modified the momentum equation assuming the entire liquid film as the control volume. The model predicts the average slug length and slug frequency at any location of the hilly-terrain pipeline, when average slug length or slug frequency at the entrance is known. The model validation with Al-Safran's (2003) data showed a reasonable match.

In Zhang et al. (2003) the model that was previously developed in Zhang et al. (2000) is compared with experimental data for a wide range of operational conditions to model slug dissipation and slug generation. Although in the model constant slug length was assumed, the slug length to slug unit length ratio is found to be a better parameter for the modeling studies.

Açikgöz et al. (1992) conducted experiments on three-phase gas-oil-water flow. They observed ten flow patterns and classified them into two groups: oil-based and water-based flows.

The effect of inclination on slug flow characteristics in three-phase gas-oil-water flow in large diameter pipelines is studied by Kang et al. (2000). Most of the measurements of slug flow are done with a camera system. However, they do not mention about any oil-water interaction in their study.

Bonizzi and Issa (2003) showed that slip between the two liquid phases plays a major role in determining the slug characteristics in their study on simulation of three-phase slug flow. They also addressed the importance of further studies on influence of water cut on the slug evolution and the changes in continuous phase in slug flow.

Shi et al. (2004) showed that gas holdup in three-phase flows can be calculated from the two-phase water-gas drift-flux parameters till a certain critical gas holdup value. From experimental measurements of Shi et al. (2003) and Oddie et al. (2003), the critical gas holdup is found to be a function of inclination angle.

Zhang and Sarica (2005) modified two-phase unified model developed by Zhang et al. (2003) to three-phase unified model by implementing closure relations for describing the mixing and inversion of liquid phases. The authors suggested further studies of the mixing status of oil and water.

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

Experimental Study

Hilly-Terrain Facility

An existing two-phase flow facility of the Tulsa University Fluid Flow Projects (TUFFP) will be modified for this study. This test facility was used previously by Al-Safran (2003) for two-phase flow in hilly-terrain pipeline. The facility is a 420-m (1378-ft) long, parallel 50.8-mm (2-in.) 76.2-mm (3-in.) diameter, horizontal steel pipelines. The test section simulates a single hilly-terrain unit of 70-ft uphill (downhill) and 70-ft downhill (uphill) sections. The inclination angles are $\pm 1°$, $\pm 2°$ from horizontal for the valley and hill configurations.

The facility is under major construction to achieve three-phase flow in the loop. New water and oil tanks have been purchased. Progressive cavity pumps for oil and water phases have been ordered from Seepex and are expected to arrive in the following month. Seepex is selling two pumps for less than the price of one pump. We appreciate their generosity. Purchase of a new three-phase separator is underway. In addition, a new hilly-terrain unit and observation stations throughout the pipeline with instrumentation will be considered to observe and measure flow characteristics. Throughout the facility, there will be totally seven observation stations including the ones on the hilly-terrain unit. The locations of the stations are already determined. Visual observation can be done in six of these stations. A schematic of the modified facility is shown in Fig. 1.

In addition to three-phase modifications, construction for spill prevention system is needed to meet the University of Tulsa's spill prevention requirements. These modifications include:

- Welding of steel pipes to prevent any possible leak.
- Usage of expandable joints to connect the steel pipes and acrylic pipes that are used for observation. The joints will take care of any expansion and shrinkage of the pipes due to ambient temperature changes.
- Placement of emergency shutdowns in case of any leakage that can be detected automatically with pressure drop.
- Installation of security cameras at critical locations to monitor the facility from the control room by a secondary facility operator.
- Installation of PVC pipes that will surround the acrylic pipes from the top and at the back in case of any rupture in the acrylic pipes.
- Usage of plastic curtains as liquid barriers at the visualization stations in case of splashes of liquid. The curtains will be used to prevent any liquid splash to the neighboring areas.
- Addition of bypass lines to the facility in parallel to the visualization stations.
- Containment berms will be put under the visualization sections to contain the spillage.
- Concrete slab will be constructed under the hilly-terrain unit for spill containment.

After the facility construction, the data acquisition system will be implemented.

Before designing the facility, a preliminary study is conducted for the facility ranges with TUFFP Unified Three-Phase Flow program. The TUFFP Unified Three-Phase Flow program gives the pressure gradient, holdup, gas-liquid and liquid-liquid flow patterns as output for the specified superficial gas, oil and water velocities with the physical properties of the fluids. The facility limitations are determined from the preliminary study.

The instrumentation for the three-phase slug flow study in hilly-terrain pipelines has its own challenges. Capacitance sensors, conductance probes, quick closing valves, pressure and differential pressure transducers are planned to be installed on the facility. High speed video will be used to capture the details of slug characteristics in three-phase flow in hilly terrain configurations. More advanced ways to measure the distribution of phases and mixing status of oil-water will be explored.

Gas-Oil-Water Flow Facility

Before the completion of construction of hilly-terrain facility, preliminary testing is decided to be done on existing gas-oil-water facility with the same test fluids. The gas-oil-water facility is recently used by Atmaca (2007) for characterization of oil-water flow in inclined pipes. The facility consists of a closed circuit loop with progressive cavity pumps, heat exchangers, metering sections, filters, test section, separator and storage tanks. The test section is attached to inclinable boom that makes inclined flow in the loop possible. The test section consists of two 21.1 m (69.3 ft) long transparent pipes with 50.8 mm (2 inch) diameter connected by a 1.2 m (4 ft) long PVC bend. The upward 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. The downward branch of the test section is designed and built similar to the upward branch. Instrumentations on the transparent pipes give the operating temperature, pressure, differential pressure and inclination. High speed video system is also used to identify the flow patterns and determine the oil-water mixing status. Schematic diagrams of the flow loop and test section are given in Fig. 2 and Fig. 3, respectively.

Three-phase inclined flow studies are decided to be done on the gas-oil-water flow loop to analyze the flow patterns and characteristics. The performance of laser beams and sensors on three-phase flow will also be analyzed.

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

- Superficial gas velocity: 0.1-7.0 m/s
- Superficial oil velocity: 0.02-1.5 m/s
- Superficial water velocity: 0.01-1.0 m/s
- Water fraction: 20, 40, 50, 60 and 80%

The preliminary testing on gas-oil-water facility is expected to be completed by November 2007 due to the weather conditions.

Test Fluids

For the experiments of three-phase flows in hilly-terrain pipelines, fresh water, air and a refined mineral oil are chosen to be used as the fluids. The refined oil, Tulco Tech 80, is chosen based on its easy separation. The physical properties of Tulco Tech 80 are given below:

- API gravity: 33.2°
- Density: 858.75 kg/m3 @ 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 are measured by Chevron labs. As shown in Figs. 4 and 5, the density and viscosity changes with temperature at three different flow rates were measured respectively.

Near Future Studies

The additions and modifications to the facility are expected to be finished by March 2008. The instrumentation of the facility is expected to be completed by May 2008.

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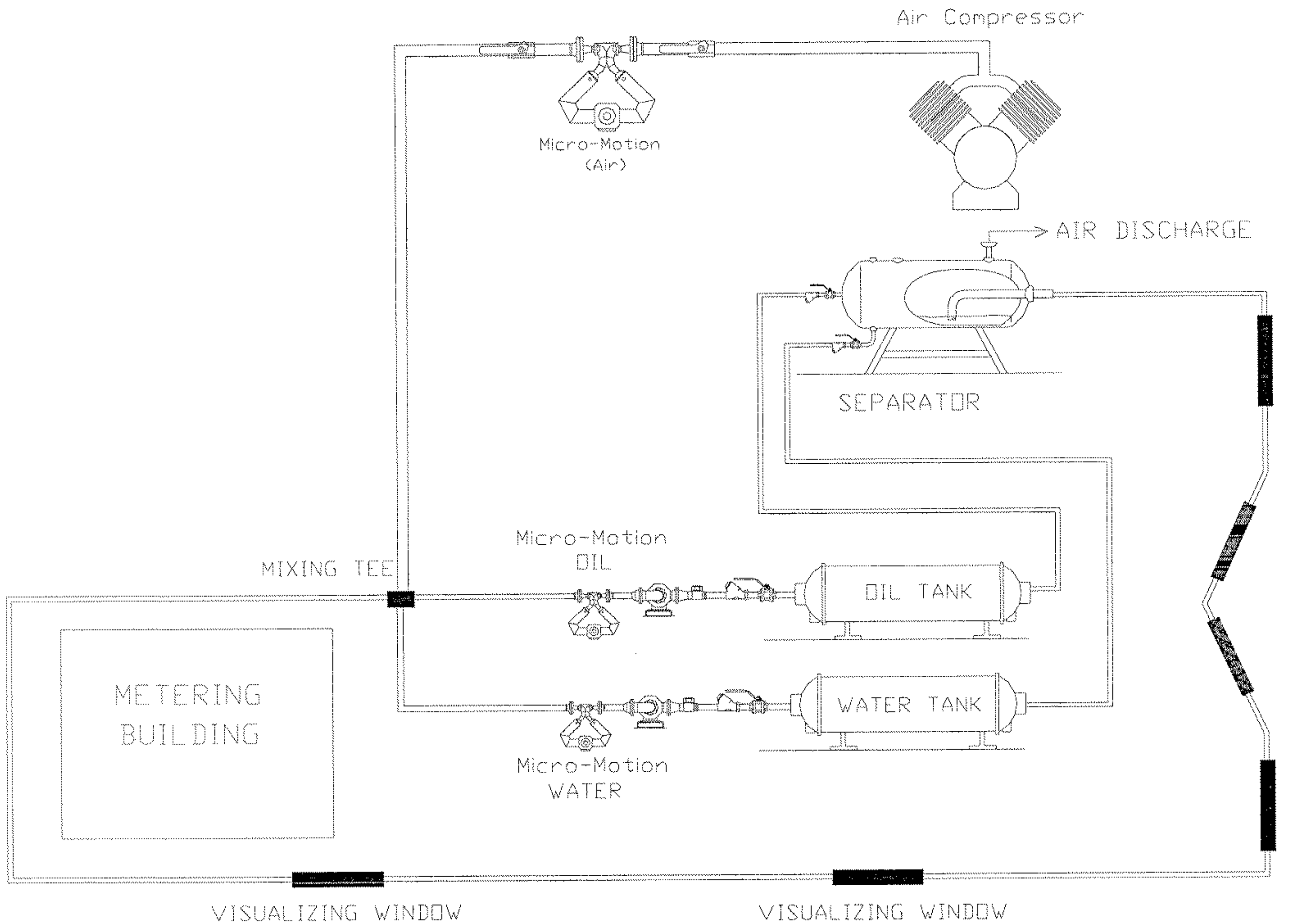

Figure 1: Modified Hilly-Terrain Facility

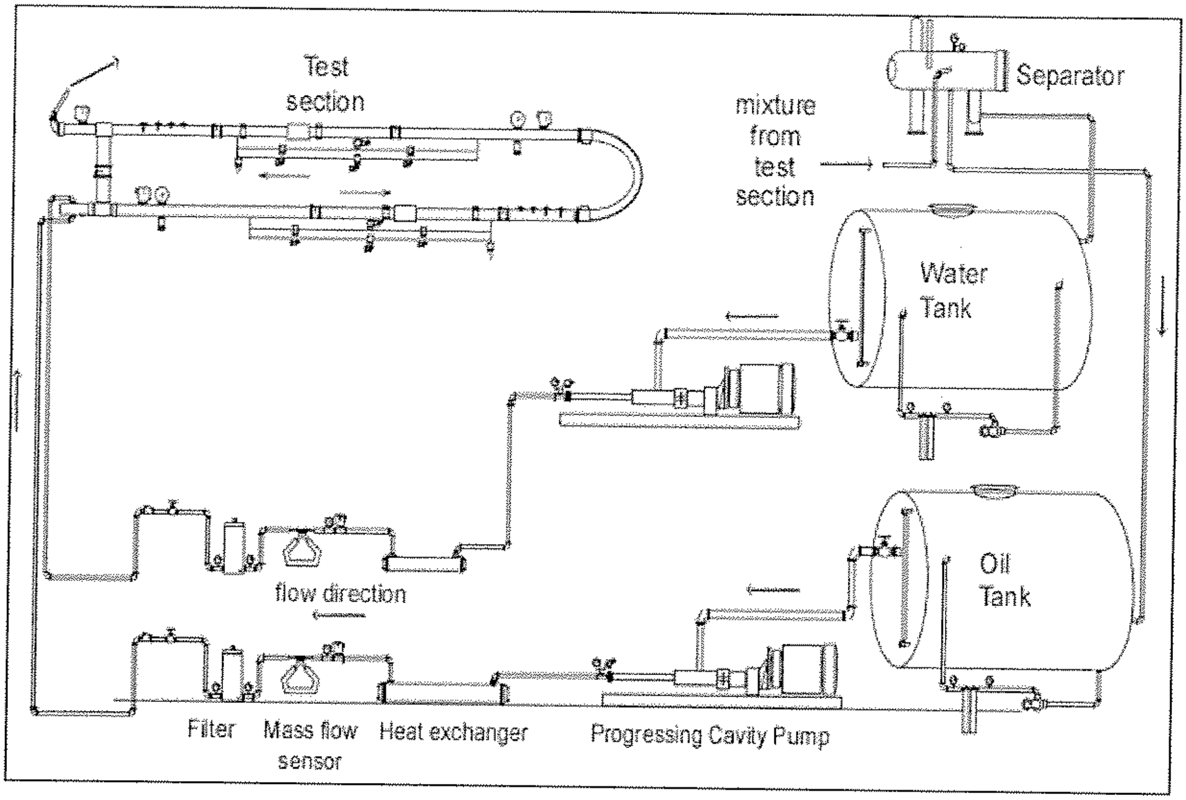

Figure 2: Gas-Oil-Water Facility Schematic

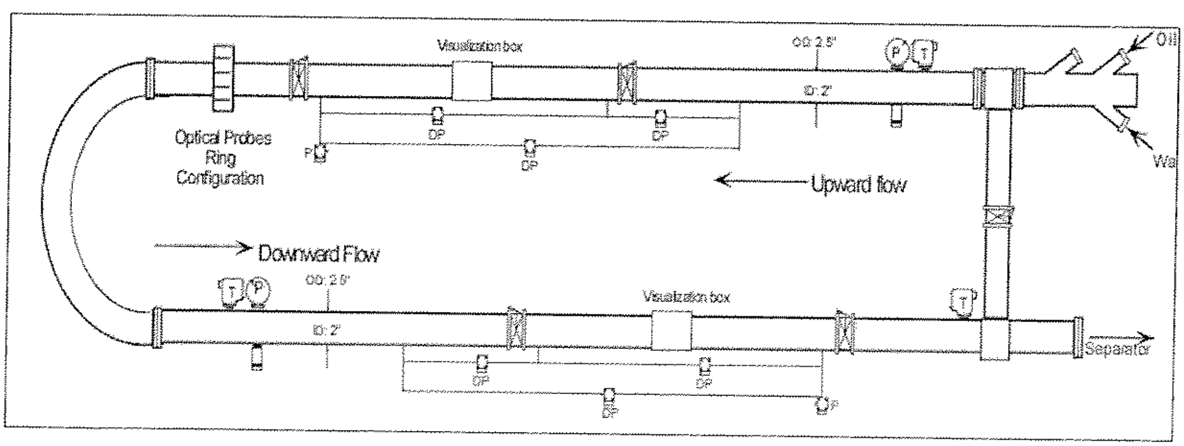

Figure 3: Gas-Oil-Water Facility Test Section Schematic

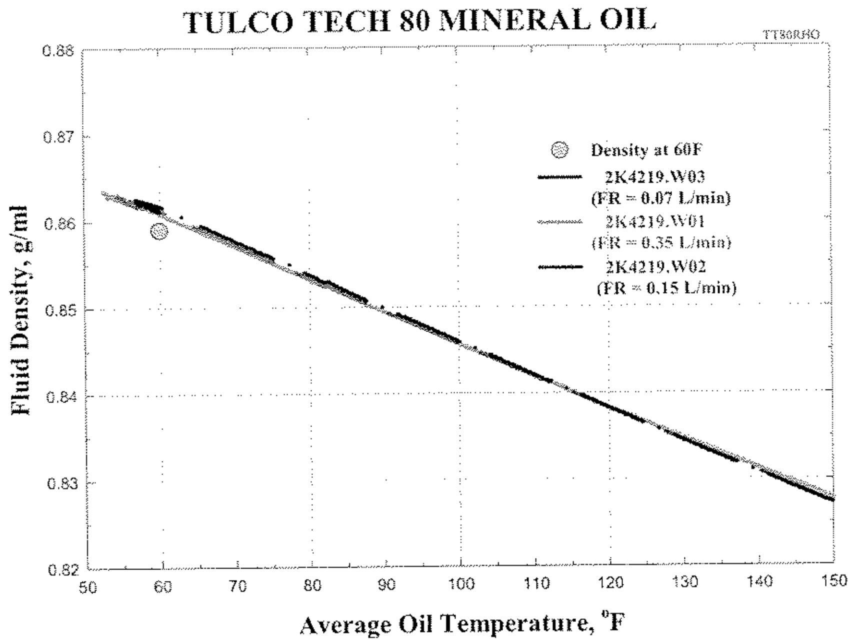

Figure 4: Tulco Tech 80 Oil Density vs. Temperature

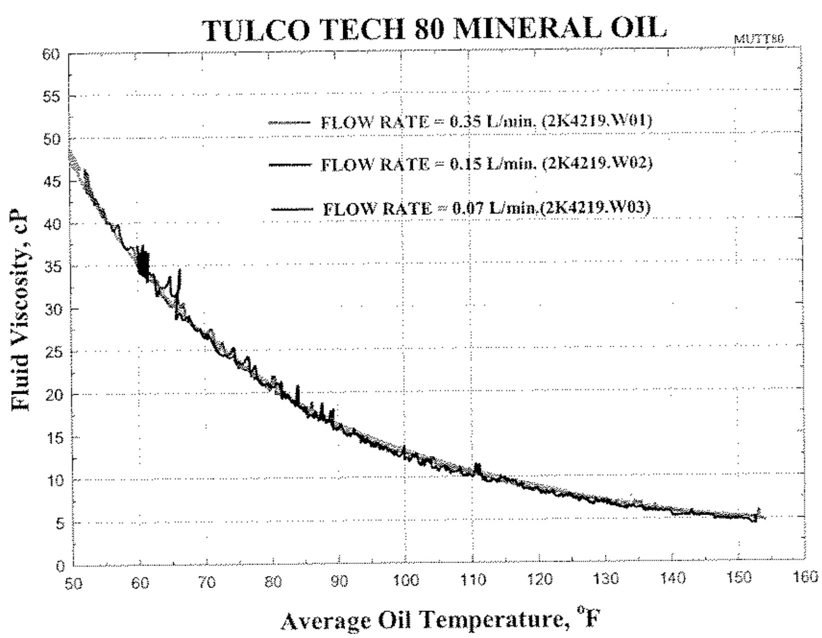

Figure 5: Tulco Tech 80 Oil Viscosity vs. Temperature

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Droplet-Homophase Interaction: Effect of Pipe Inclination on Entrainment Fraction

Al-Sarkhi Abdel

Advisory Board Meeting, November 6, 2007

Outline

- Introduction
- Review of Previous Studies by TUFFP
- Evaluation of Chen's Model
- Effect of Pipe Inclination
- Summary & Conclusion

Introduction

- Multiphase Flow Mechanistic Models Are Tools in Multiphase Design and Applications
  - Pressure Gradient
  - Liquid Holdup
  - Temperature Gradient
  - Others

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Introduction

- Closure Relationships Required by Mechanistic Multiphase Flow Models (e.g. TUFFP Unified Model)
  - Interfacial Friction Factor
  - Droplet Entrainment Fraction
  - Slug Translational Velocity
  - Others

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Introduction

- Droplet Entrainment in Stratified Flows and Annular Flows
- Mass Flow Rate Ratio of Liquid Droplets in Gas Core to Total Inlet Liquid Flow Rate

$$F_E = \frac{(W_L - W_{LF})}{W_L} = \frac{W_{LE}}{W_L}$$

- Droplet Atomization Rate = Droplet Deposition Rate for Quasi-equilibrium Condition (Fully Developed Region)

TUFFP (Stage I: Sensitivity Study)

- F_E has Most Significant Effect on Predictions of Pressure Gradient and Liquid Holdup
- Accurate Entrainment Fraction Correlation is Crucial for the Success of Multiphase Flow Mechanistic Models

Stage II: Model Development (Chen, Oct. 2005 ABM)

- Sufficiently Large Local Shear Stress at the Interface to Overcome the Containing Effect of Surface Tension
- Hutchinson & Whalley (1973) Described Entrainment Process by a Single Dimensionless Group, S (= $\tau_i\, l / \sigma$)
- Entrainment Rate (R_A) = Deposition Rate (R_D)
- Collapsed Data of Droplet Concentration onto a Single Curve
- Assumptions of Interfacial-shear-dominated Atomization and Quasi-equilibrium State are Valid

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TUFFP (Stage II: Model Development)

- Droplet Atomization
  - $R_A = \Gamma(\tau_i\, \delta / \sigma)$
  - Assuming Film Thickness << Pipe ID
  - $\delta = (1 - F_E)\, V_{SL}\, D / (4\, V_F)$
  - $\tau_i = ½\, f_i\, \rho_g\, (V_c - V_F)^2$

$$R_A = k_A \rho_L \frac{f_I \rho_G V_C^2 V_{SL} D(1 - F_E)}{8\sigma V_F}$$

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TUFFP (Stage II: Model Development)

- Droplet Deposition
  - Andreussi & Azzopardi Considered Turbulence Diffusion as Dominant Mechanism in Vertical Flow
  - $R_D = k_D C$
  - Assume Uniform Droplet Distribution Across Pipe and No Slippage Between Gas and Drops
  - $C \approx \rho_L F_{E,V} V_{SL} / V_C$
  - $R_D \approx k_D \rho_L F_{E,V} V_{SL} / V_C$

Approximation

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TUFFP (Stage II: Model Development)

- $R_A = R_D$

$$\frac{F_{E,V}}{1 - F_{E,V}} = k \frac{f_I \rho_G V_C (V_C - V_F)^2 D}{8 \sigma V_F}$$

where $k = k_A / k_D$

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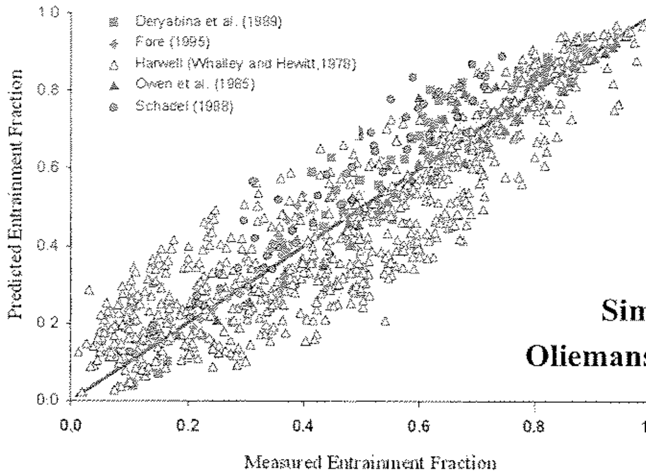
TUFFP (Stage II: Model Development-Vertical Annular Flow)



Similar to Oliemans et al. (1986)

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TUFFP (Stage II: Model Development)

- Horizontal and Inclined Flows, Asymmetric Distribution of Fluid
- Average Film Thickness Corrected by Pipe Circumferential Wetted Fraction Θ
- $\delta = (1 - F_E)\ V_{SL}\ D / (4\ V_F\ \Theta)$

$$\frac{F_{E,H}}{1-F_{E,H}} = k\frac{f_I \rho_G V_C (V_C - V_F)^2 D}{8\sigma V_F \Theta} = k\psi$$

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

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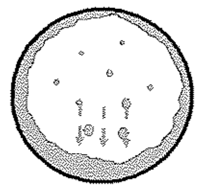
TUFFP (Stage II: Model Development)

- Gravitational Force Also Promotes Settling of Entrained Droplets
- Proposed Use of "Inclination Angle Factor" k_θ to Account for Settling Effect
- $k_\theta = \Gamma(Fr_\theta$, etc)

$$Fr_\theta = \sqrt{\frac{\rho_G V_{SG}^{\;2}}{(\rho_L - \rho_G) g D \cos\theta}}$$



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TUFFP (Stage II: Model Development)

- Determine Functionality of k_θ by Trial-and-error by Fitting Calculated F_E Against Experimental F_E

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

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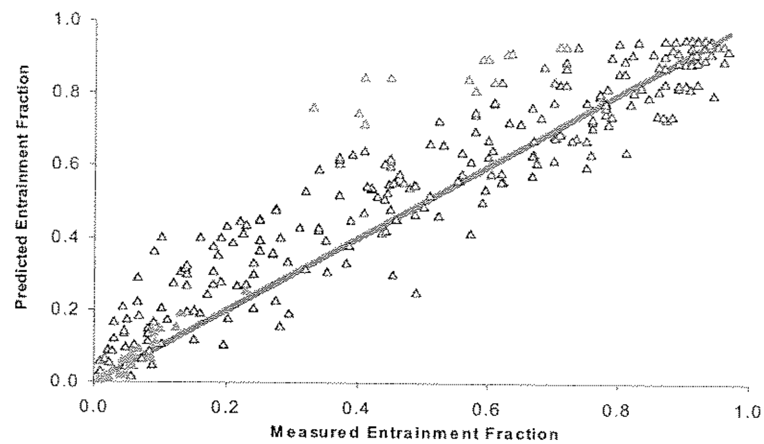
TUFFP (Stage II: Model Development-Horizontal Flow)



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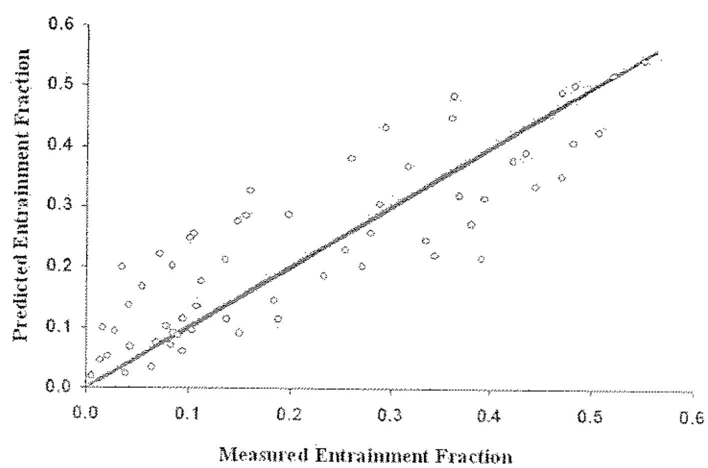
TUFFP (Stage II: Model Development-Inclined Flow)



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Entrainment Data Bank

- Vertical Flow

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

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Entrainment Data Bank ...

- Horizontal and Inclined 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. (1996)	0.026	0 ~ 75	Air/Water	60
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

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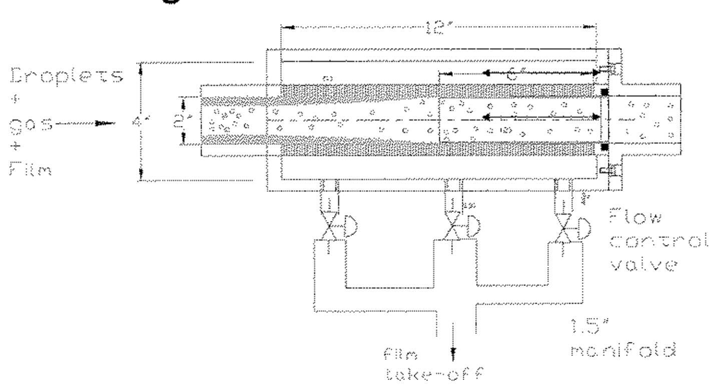
Model Evaluation …

- Model Predict F_E with Reasonable Accuracy for Vertical
- k_θ Gives Unreasonable Value at High Reynolds Number of Liquid Film
- Uses Implicit Parameters That Require Solving of Other Closure Relationships (NOT General)
- Single Experiment for Inclined Data of Ousaka et al. in 26 mm Pipe at 5 Different Angles
- HARWELL Databank, Over 700 Data Points for Vertical Flow in 6 mm – 31.6 mm Pipe Diameter

Effect of Pipe Inclination-Stage III

- Propose Experimental Investigation
  - D=50.8 mm
  - Angles from 0° to +14° and to -90 °



Effect of Pipe Inclination - Experimental

- Similar to Hay et al., Azzopardi et al., Simmons and Hanratty and Al-Sarkhi and Hanratty
- Liquid Film Pushed out through Porous Section by Pressure in Pipe
- Large Inertia of Droplets Prevent Them From Being Removed From Core Flow
- Along Sleeve Will be Inserted Very Close to Liquid Film - Thin Film Will Pass Underneath the Sleeve and Droplets Will Never See Holes of Porous Section

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Effect of Pipe Inclination - New Parameters

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

$$Fr_{SL} = \sqrt{\frac{\rho_L V_{SL}^{\;2}}{(\rho_L - \rho_G) g D \cos\theta}}$$

$$Fr_{SG} = \sqrt{\frac{\rho_G V_{SG}^{\;2}}{(\rho_L - \rho_G) g D \cos\theta}}$$

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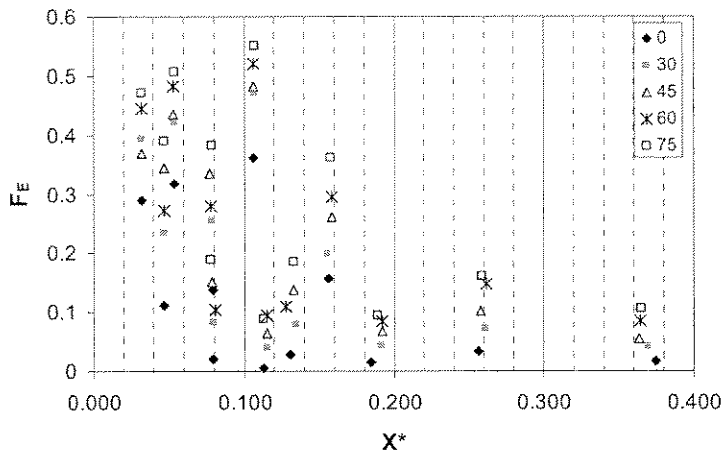
Entrainment Fraction at Different Angles (Data of Ousaka et al. 1996)



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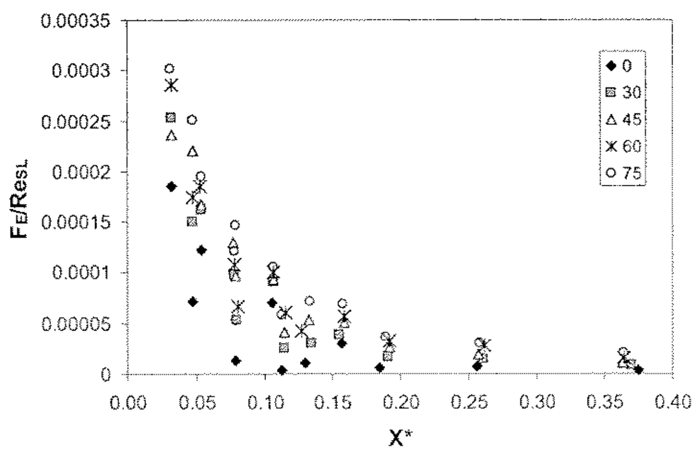
Entrainment Fraction at Different Angles (Data of Ousaka et al. 1996)



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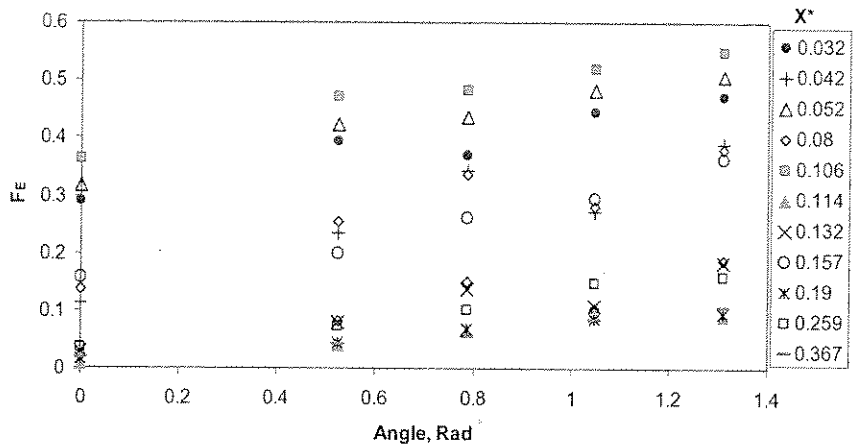
Entrainment Fraction at Different Angles

The legend is not arranged



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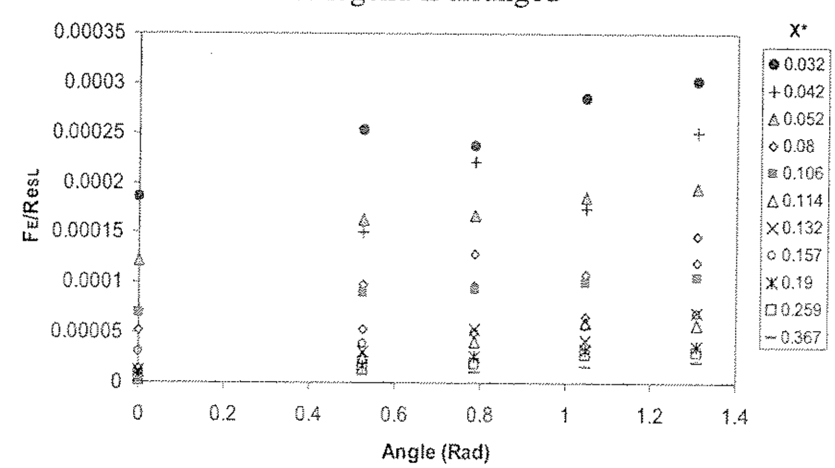
Normalized Entrainment Fraction at Different Angles

The legend is arranged



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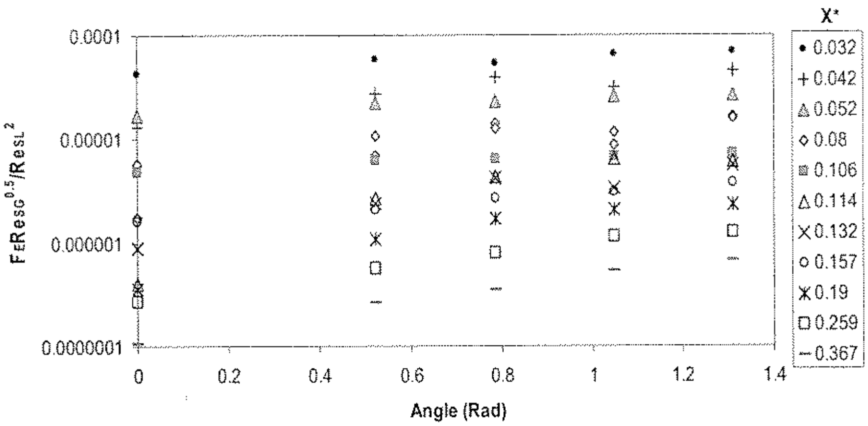
Normalized Entrainment Fraction at Different Angles

The arrangement of the legend is clear



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Effect of Pipe Inclination: New Parameters

- **Entrainment Follows Almost Linear Relations**
- **11 Values of *X** with 11 Relations**

$$\frac{F_E}{\mathrm{Re}_{SL}} = A\theta + B$$

At certain X^*

$$\frac{F_E}{\mathrm{Re}_{SL}} = \left\{6\times10^{-6} X^{*-0.8617}\right\}\theta + \left\{4\times10^{-7} X^{*-1.7608}\right\}$$

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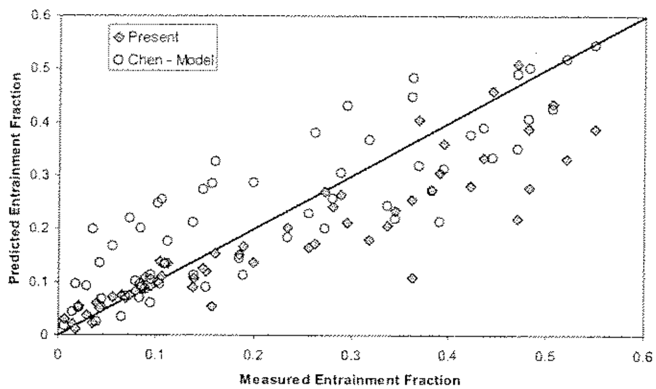
Based on Inclined Data from Ousaka 1996 Experiment



Model	Chen	Eq. 24
ε_1	0.475	0.003
ε_2	0.682	0.315
ε_3	1.08	0.789
ε_4	0.014	-0.043
ε_5	0.067	0.054
ε_6	0.083	0.091

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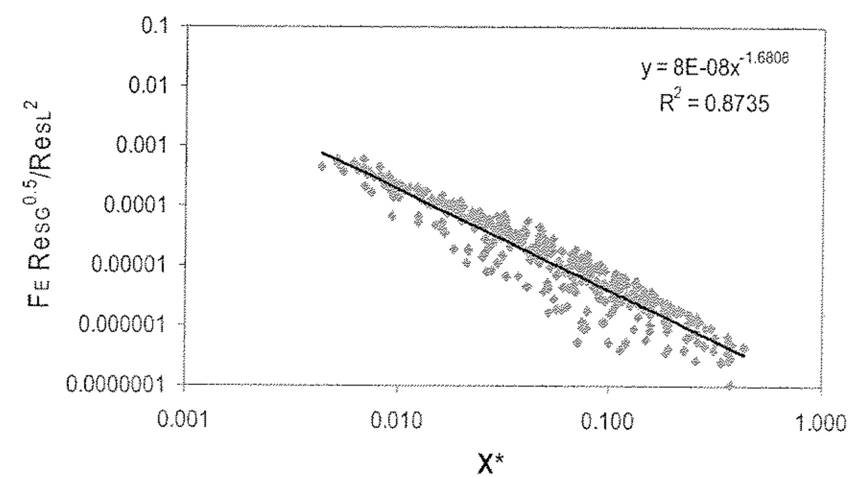
Entrainment Fraction Parameter - All Points (Horizontal, Inclined and Vertical pipes)



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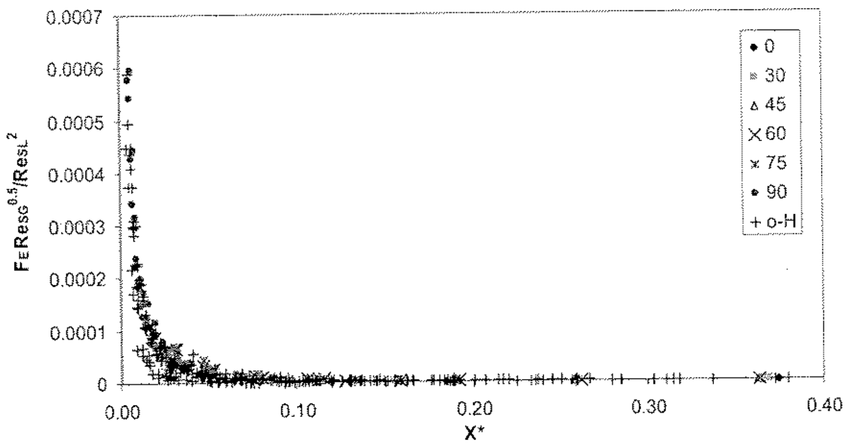
Linear scale-Vertical, Horizontal and inclined



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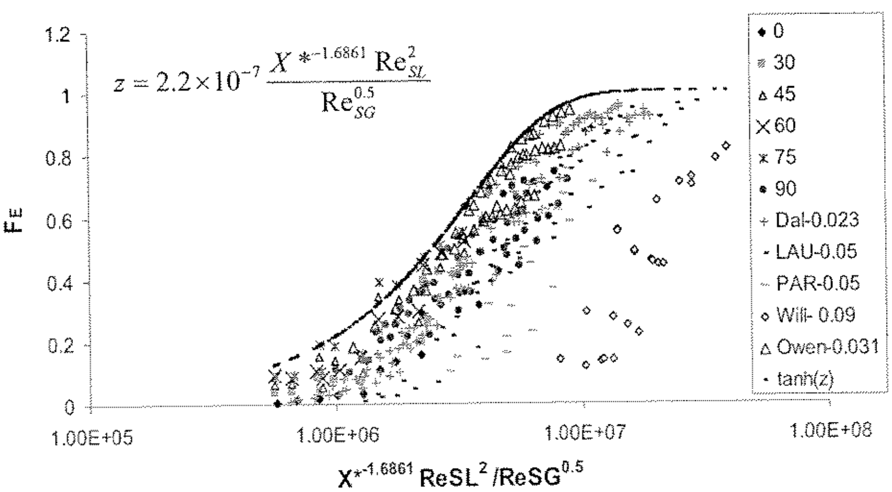
Entrainment Fraction (Horizontal, Inclined and Vertical pipes)



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Summary

- More Accurate Entrainment Fraction Model is Needed for All Inclination Angles
- Available Models in Literature
  - Reasonable Prediction for Vertical flows
  - Scattered Results for Horizontal flows
  - No Model for Inclined Flows- *Chen's Model is the only one*
- More Accurate Entrainment Fraction Measurements is Needed for All Inclination Angles

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Summary

- Entrainment Fraction Shows Linear Trend With Inclination Angle at Same Values of *X**
- Entrainment Fraction for All Inclinations Follows a Tangent-Hyperbolic Relation with *Z* Parameter

$$z = 2.2\times10^{-7}\,\frac{X^{*-1.6861}\,\mathrm{Re}_{SL}^{2}}{\mathrm{Re}_{SG}^{0.5}}$$

- Explicit Parameters Such as X*, Re_{SG} , Re_{SL} Could be Used to Predict Entrainment Fraction for All Inclinations

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Droplet-Homophase Interaction: Effect of Pipe Inclination on Entrainment Fraction

Al-Sarkhi Abdel

Abstract

A new entrainment fraction model was proposed by Xianghui Chen (TUFFP ABM October 2005) which is claimed to be applicable for all inclination angles. Reasonable agreement was obtained between the new model predictions and published entrainment data. It has been noticed that for horizontal and inclined pipeline and at a large liquid film Reynolds number the entrainment fraction is under-predicted. In addition to the previous mentioned disadvantage of this model, the model uses implicit parameters which need another models or closure relationships. This procedure most likely carries uncertainties of the other closure relationships. The only inclined data available in literature is presented in a paper by Ousaka 1996 in 26 mm pipe and on which the Chen model was formulated. More data are needed at larger pipe diameter and different pipe inclination. New dimensionless parameters were found to be significant in predicting the effects of pipe inclination are presented.

Introduction

An annular flow pattern can exist when gas and liquid flow at a high velocity in a pipe. Part of the liquid flows along the wall as a film and part, as droplets entrained in the gas phase. There is a liquid transfer between the wall and the gas core, whereby droplets deposit at the wall and are formed by atomization of the wall film. Under equilibrium conditions the rate of atomization, R_A, equals the rate of deposition, R_D. A critical parameter needed to understand the behavior of an annular flow is the fraction of the liquid entrained as droplets, F_E, which is related to R_A and R_D. A central problem in analyzing annular flows is the prediction of drop size and entrainment. The rate of deposition is usually defined in terms of a deposition constant, K_D, ($R_D = K_D C$) where C is the droplet concentration in the gas. For vertical flows C equals the bulk concentration of drops and, for most cases, K_D is related to the root-mean-square of the velocity fluctuations of the drops. The ratio of the drop turbulence to the fluid turbulence decreases with increasing drop diameter because of the increase in the inertial time constant of the drops. The influence of entrained drop in horizontal annular flows is more complicated. The rate of deposition is changed because gravitational settling causes an asymmetric distribution of droplets/film thickness and contributes directly to the local rate of deposition. The influence of gravity on deposition and on the asymmetric distribution of drops increases with increasing droplet size. The focus of the next stage is to examine the effect of pipe inclination and diameter on entrained droplet in annular flows. Such information is critically important in predicting the behavior of large diameter pipes especially with the very limited data available in literature.

Most multiphase flow prediction models (including the TUFFP unified mechanistic model) 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 accuracy and physical completeness of these closure relationships determine the performance of a multiphase flow model. Nevertheless, the literature reveals that the empirical closure relationships may not contain sufficient physics of multiphase flow. Thus, systematic examination and further refinements of these closure relationships can substantially improve the performance of multiphase mechanistic models.

A sensitivity study (March 2005 ABM) was carried out to investigate the influence of individual closure relationships on the outcomes of a multiphase mechanistic model. The sensitivity study demonstrated that in stratified and annular flow the variation of droplet entrainment fraction can significantly affect the predicted pressure gradient and liquid hold-up. Therefore, it is imperative to use an accurate predictive model for entrainment fraction.

Chen (2005b) started from the assumption that droplet atomization and deposition processes reach equilibrium condition when the flow is fully developed. Turbulence of the gas core and liquid surface tension are considered dominant mechanisms that govern the entrainment process. It is also assumed that droplet deposition is mainly due to turbulence diffusion. Model development starts from vertical annular flows. For vertical annular flows, the required coefficient in the model is correlated by using a large databank collected from vertical annular flow literature (Table 1). Most of the data is from Harwell data bank for pipe diameter range from 6 mm to 31.8 mm. scaling up the result of such small pipe diameter to larger diameter is questionable. With the recognition of gravitational settling effects, the model developed for vertical flow is extended to horizontal and inclined flow by introducing an inclination angle factor. This factor is empirically determined by correlating entrainment data of horizontal and inclined flows obtained from the literature. The only inclined flow data available in literature and on which Chen's model was based is that from Ousaka et al. (1996). The Ousaka et al. experiment was conducted in 26 mm pipe at five different angles 0, 30, 45, 60 and 75 degrees and the number of data points were 60 points.

The main objective of this stage is to understand the effect of pipe inclination on entrainment and to develop more reliable closure relationships for inclined pipeline which is preferred to be explicit parameters dependent. Measurement of entrainment fraction in larger diameter pipe at different inclination angle is another objective of this stage.

Review-Chen Model (Presented in October 2005 ABM)

Under equilibrium conditions the rate of atomization, R_A, equals the rate of deposition, R_D.

$$R_A = R_D. \tag{1}$$

Zuber (1962) and Hutchinson and Whalley (1973), proposed that droplet entrainment is dominantly governed by two mechanisms: turbulence and surface tension. The first mechanism is the breaking force and the second tends to sustain liquid in the continuous phase. Using the approach employed by Okawa et al.(2002), the following relationship is suggested

$$R_A \sim \Gamma\left(\frac{\tau_I l}{\sigma}\right) = k_A \rho_L \frac{\tau_I \delta}{\sigma}. \tag{2}$$

Where l is the characteristic length. Chen used the liquid film thickness, δ, as a characteristic length, k_A is the coefficient of atomization rate. The interfacial shear stress, τ_I, is $\tau_I = \frac{1}{2} f_I \rho_G (V_C - V_F)^2$

Thus, the atomization rate is expressed as

$$R_A = k_1 \rho_L \frac{f_I \rho_G (V_C - V_F)^2 \delta}{2\sigma}. \tag{3}$$

A) Vertical Annular Flow

In vertical annular flow, the liquid film thickness can be determined by

$$\delta = \frac{(1 - F_E) V_{SL} D}{4 V_F}. \tag{4}$$

Combining equations (3) and (4) yield

$$R_A = k_1 \rho_L \frac{f_I \rho_G V_C^{\,2} V_{SL} D (1 - F_E)}{8 \sigma V_F}. \tag{5}$$

Andreussi and Azzopardi (1983) considered turbulence diffusion as the dominant mechanism for droplet deposition in vertical annular flow. Using a quasi-equilibrium droplet concentration in the gas core, C, the deposition rate is expressed as

$$R_D = k_2 C. \tag{6}$$

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

$$C = \rho_L \frac{F_E V_{SL}}{V_C}. \tag{7}$$

Thus,

$$R_D = k_2 \rho_L \frac{F_E V_{SL}}{V_C}. \tag{8}$$

The droplet atomization and deposition rates reach equilibrium when the flow is fully developed. Equating (5) to (6), then the entrainment fraction for vertical annular flow is determined by

$$\frac{F_E}{1 - F_E} = k \frac{f_I \rho_G V_C (V_C - V_F)^2 D}{8 \sigma V_F}. \tag{9}$$

Where $k = k_A/k_D$.

Using the vertical annular flow data sets listed in Table 1, the coefficient k in Eq. (9) has been correlated as

$$k = 1.5\times10^{-7}\,\mathrm{Re}_{SL}\left(\frac{\rho_G}{\rho_L}\right)^{0.15}\left(\frac{\mu_L}{\mu_G}\right)^{1.2}. \tag{10}$$

B) Horizontal and inclined flows

Due to the asymmetric distribution of fluid in horizontal and inclined flows, calculation of the average film thickness is corrected by the pipe circumferential wetted fraction (Θ). This wetted fraction is predicted by using the Grolman correlation (1994). The liquid film thickness is modified from (4) and becomes

$$\delta = \frac{(1-F_E)V_{SL}D}{4V_F\Theta}. \tag{11}$$

Where Θ is the pipe circumferential wetted fraction. Thus, Eq. (9) is revised as Eq. (12) for horizontal and inclined flow.

$$\frac{F_E}{1-F_E} = k\frac{f_I\rho_G V_C(V_C - V_F)^2 D}{8\sigma V_F\Theta}. \tag{12}$$

The gravitational force not only causes an asymmetric liquid film configuration, but also promotes the settling of entrained droplets to the liquid film. To account for this gravitational settling effect, Chen proposed the use of a correction factor known as the "inclination angle factor" k_θ which he argued must be at least a function of a modified Froude number Fr_θ, that is

$$k_\theta = \Gamma(Fr_\theta, etc). \tag{13}$$

The modified interfacial Froude number, Fr_θ, takes the form,

$$Fr_\theta = \sqrt{\frac{\rho_G V_{SG}^{\;2}}{(\rho_L - \rho_G)gD\cos\theta}}. \tag{14}$$

Attempts to incorporate Eq. (13) into Eq. (8) were not successful. Instead, k_θ is applied to the predictions given by Eq (12) to obtain the entrainment fraction for horizontal and inclined flow. Using the data sets listed in Table 2, k_θ is correlated by

$$k_\theta = \exp\left(-0.036\frac{\mathrm{Re}_{LF}^{\;0.49}}{Fr_\theta}\right). \tag{15}$$

Where Re_{LF} the Reynolds is number of the liquid film and is defined as:

$$\mathrm{Re}_{LF} = \frac{\rho_L V_F\delta}{\mu_L} \tag{16}$$

The entrainment fraction in horizontal and inclined flow is given by

$$F_E = k_\theta F_{E(12)}. \tag{17}$$

From Eqs. (12) and (17):

$$F_E = k_\theta\frac{k\psi}{1+k\psi}. \tag{18}$$

Where

$$\psi = \frac{f_I\rho_G V_C(V_C - V_F)^2 D}{8\sigma V_F\Theta}.$$

It is clear that k_θ and Θ are equal to 1 for vertical flow, so that Eq. (18) is equivalent to Eq. (9).

Evaluation of the Model

The data sets included in the droplet entrainment fraction databank are listed in Tables 1 and 2.

Chen model was implemented in the TUFFP unified model. Figures 1-3 present comparisons of the predictions and the data. Figure 1 shows that the unified entrainment model gives good predictions of entrainment fraction for vertical annular flow. The predictions are similar to the results of the Oliemans et al. (1986) model and better than Ishii and Mishima (1989), Wallis (1968) model. Good agreement is also observed for horizontal stratified and annular flow, as seen in Fig. 2, except for the over-prediction of several points (shaded) where the gas superficial velocity is very high (greater than 130 m/s).

Statistical parameters of the above analysis are summarized in Table 3. The statistical parameters in Table 3 are defined in Appendix A:

In summary, the following evaluation comments on Chen's model can be made:

- In general, Chen model predict the entrainment fraction for inclination angles from horizontal to vertical with reasonable accuracy but not for all cases.

- Gravity causes an asymmetric distribution of drops (even droplet size) in the gas core; i.e. drop concentration in bulk is different from that close to the interface. Paras and Karabelas (1991) showed experimentally a decrease in drop concentration from the interface to the bulk. Pan and Hanratty (2002) also showed an exponential decay of droplets concentration from the bottom to top. The assumption of constant concentration made in Eq. 7 is not reasonable.

- The entrainment fraction factor, k_θ, gives unreasonable result at extreme values of Reynolds number of the liquid film, Re_{LF}, due to the exponential nature of the correlation, e.g. at very large Re_{LF} the entrainment fraction is under-predicted.

- The model uses implicit parameters that require solving of other closure relationships, therefore most likely, carries uncertainties of the other closure relationships within the model used (unified model in this case)

- The model based on a single experiment for the inclined data of Ousaka et al. (1996) in a 26 mm pipeline at five different angles and 60 data points only. Scaling up the entrainment data in the 26 mm pipe and extrapolating and interpolating the whole range of inclination based on single experiment is questionable.

- HARWELL data bank (1978) used by Chen (over 700 data points) for vertical flow in 6 mm – 31.6 mm pipe diameter. Scaling up results of 6 mm entrainment data needs to be verified.

The Inclination Effect

A plan of modifying Chen model or developing a new model for the effect of pipe inclination on entrainment has been started through two steps:

A) Experimental investigation

More experimental measurement of the entrainment fraction in inclined pipes of larger diameter than 26 mm (Ousaka et al. 1996) is needed. For that purpose a new test section will be installed in TUFFP 50.8 mm flow loop. The procedure for measuring the entrainment in this section is done by removing the liquid film from the wall of the pipe and allow the droplets to pass through the gas phase. Subtracting the liquid film flow rate from the total liquid flow rate will give the entrained flow rate. This was done by using a specially designed test section as shown in Fig. 4 similar to the one used by Hay et al. (1996), Azzopardi et al. (1996), by Simmons and Hanratty (2001) and Al-Sarkhi and Hanratty (2002) in there measurement of drop size distribution. The flow passes through a porous section and the liquid film, which travels at lower velocity than the gas and droplets, is pushed out through the porous section by the pressure in the pipeline. The droplets travel at a velocity close to the gas velocity so their large inertias prevent them from being removed from the core flow. In addition, a long sleeve will be inserted very close to the liquid film and will be pushed in and out to make sure that the thin film will pass underneath the sleeve and the droplets will never see the holes of the porous section so they will be not taken off or deviated toward the holes. The film take off rate will be controlled by valves.

Measurements of entrainment fraction will be conducted and result will be compared with Ousaka et al. (1996) and the entrainment model of Chen.

B) Searching for the most significant dimensionless parameters

Many of the parameters involved in most of the correlation in literature are scattered and not grouped in dimensionless numbers which make it very difficult to understand and improve their model (for example Oliemans et al. (1986); Okawa et al. (2002)).

The dimensionless parameters will be used in modifying and revising Chen model. New closure relation may be needed. The equilibrium of drop atomization and deposition equation will be used.

The dimensionless parameter, X^*, is defined as the ratio of the Modified Froude number, Fr_{SL}, based on the superficial liquid velocity to the Modified Froude number, Fr_{SG}, based on the superficial gas velocity.

$$X^* = \frac{Fr_{SL}}{Fr_{SG}}. \qquad (19)$$

Where Fr_{SG} and Fr_{SL} are defined as

$$Fr_{SG} = \sqrt{\frac{\rho_G V_{SG}^{\ 2}}{(\rho_L - \rho_G) g D \cos\theta}} \,. \tag{20}$$

$$Fr_{SL} = \sqrt{\frac{\rho_L V_{SL}^{\ 2}}{(\rho_L - \rho_G) g D \cos\theta}} \,. \tag{21}$$

Thus, X^* can be written as

$$X^* = \sqrt{\frac{\rho_G}{\rho_L}}\frac{\dot{m}_L}{\dot{m}_G} \,. \tag{22}$$

Using the only inclined data available (Ousaka et al. 1996) a special trend of the entrainment fraction is shown in Fig. 5 and 6. Entrainment at different angles but similar X^* gathered in groups. Figure 7 shows clearly the effect of pipe inclination at different angles at same X^*, the entrainment follows almost linear relations but still the legend are not arranged properly. Figure 8 shows a clear trend for the entrainment fraction and Reynolds number based on the superficial liquid velocity, F_E/Re_{SL} ratio. The legends now are all properly arranged, the highest X^* has the lowest value of F_E/Re_{SL}. Similar trend is shown in Fig. 9 if the combination of $F_E Re_{SG}^{0.5}/Re_{SL}^{2}$ is plotted against the pipe inclination. Where Re_{SG} is the Reynolds number based on the superficial gas velocity. A linear relation of F_E/Re_{SL} and pipe inclination can be written as

$$\frac{F_E}{Re_{SL}} = A\theta + B \,. \tag{23}$$

Where θ is the pipe inclination angle in radian and A and B are constants. The above equation has been found at the 11 values of X* available then 11 values of A and B were found then one equation for A and another for B as a function of X* were found using the best trend line which fits the data. Thus, one equation that represents the 11 straight lines in Fig. 8 is written as in Eq. 24

$$\frac{F_E}{Re_{SL}} = \left\{6\times10^{-6} X^{*-0.8617}\right\}\theta + \left\{4\times10^{-7} X^{*-1.7608}\right\} \tag{24}$$

Figure 10 shows a comparison between Eq. 24 and Chen model for the inclined data of Ousaka 1996. Equation 24 shows better agreement with the Osauka data than Chen model especially at lower entrainment fraction < 0.3. A comparison with Chen model for the six statistical parameters is shown in Table 3.

Figures 11 and 12 show a self similar behavior for the dimensionless group, $F_E Re_{SG}^{0.5}/Re_{SL}^{2}$, against the parameter X^* for all positions (horizontal, inclined and vertical) of the data banks listed in Table 1 and 2.

Using the best trend line that fits the data, a single equation for entrainment fraction at all inclination from 0 to 90 could be extracted as shown on Fig. 11.

$$\frac{F_E \, Re_{SG}^{0.5}}{Re_{SL}^{2}} = 8\times10^{-8} X^{*-1.6808} \,. \tag{25}$$

Figure 13 shows that entrainment fraction, F_E, plotted against the parameters of the best trend line that fits the data in Fig. 11 (variables of Eq. 25). It seems that the entrainment fraction follows a tan hyperbolic like relation.

$$F_E = \tanh\left(2.2\times10^{-7}\frac{X^{*-1.6861} Re_{SL}^{2}}{Re_{SG}^{0.5}}\right). \tag{26}$$

Ishii and Mishima 1989 have found similar result with different independent variable for the tan hyperbolic function as shown in Eq. 27.

$$F_{E(Ishii)} = \tanh\left(7.25\times10^{-7} We^{1.25} Re_{SL}^{0.25}\right). \tag{27}$$

Where, We is the effective Weber number based on the pipe diameter as a length scale (Eq. 28) and Re_{SL} is the Reynolds number based on the superficial liquid velocity (Eq. 29).

$$We = \frac{\rho_g U_{SG}^2 D}{\sigma}\left(\frac{\Delta\rho}{\rho_g}\right)^{1/3} . \tag{28}$$

$$Re_{SL} = \frac{\rho_L U_{SL} D}{\mu_L} . \tag{29}$$

Summary and Conclusion

Multiphase flow mechanistic models are strongly affected by Entrainment fraction. The entrainment models in the literature are limited in terms of their application range and accuracy. Very limited entrainment data available in inclined pipe and more data are needed. Abundant of entrainment data in vertical small diameter pipes are available in literature. These data has been used by many. Scaling up these data to larger diameter is questionable.

An entrainment fraction model which can be used for inclination angles from horizontal to vertical is proposed by Chen (ABM 2005) with some limitations. Chen's Model based on the hypothesis that droplet atomization and deposition processes reach equilibrium condition in a fully developed flow. Turbulence of the gas core and liquid surface tension are considered dominant mechanisms that govern the entrainment process. It is also assumed that droplet deposition is mainly due to turbulence diffusion. Model development starts with vertical annular flow and then extends to horizontal and inclined flows. For vertical annular flow, the required coefficient in the model is correlated by using a large databank collected from vertical annular flow literature. With the recognition of gravitational settling effects, the model developed for vertical flow is extended to horizontal and inclined flow by introducing an inclination angle factor. This factor is empirically determined by correlating entrainment data of horizontal and inclined flows obtained from the literature. The model was validated against a variety of data sets from the literature and reasonable agreement has been observed in some cases.

Several limitations of Chen's model have revealed. Besides the using of implicit parameters for prediction, the entrainment fraction is under predicted for large values of Re_{LF}.

New parameters for the entrainment fraction variation with pipe inclination have been found. The entrainment fraction shows a linear trend with the inclination angle at same values of X^*. Several Explicit dimensionless parameters such as X^*, Re_{SG} and Re_{SL} have shown strong relation with the entrainment fraction as shown in Fig. 11. These explicit parameters can be used to predict the effect of pipe inclination on the entrainment fraction as shown in Fig. 10. A simple correlation has been developed based on the linear relation of the entrainment fraction and the pipe inclination at constant X^* (Eq. 24). Comparing with Chen model this correlation shows better agreement with Ousaka et al. (1996) data.

Appendix A: Statistical parameters in Table 3

Average relative error,

$$\varepsilon_1 = \frac{1}{N}\sum_{i=1}^{N} e_{r,i}\,. \tag{A-1}$$

Absolute average relative error,

$$\varepsilon_2 = \frac{1}{N}\sum_{i=1}^{N} \left|e_{r,i}\right|\,. \tag{A-2}$$

Standard deviation about average relative error,

$$\varepsilon_3 = \sqrt{\frac{\sum_{i=1}^{N}\left(e_{r,i} - \varepsilon_1\right)^2}{N-1}}\,. \tag{A-3}$$

Average actual error,

$$\varepsilon_4 = \frac{1}{N}\sum_{i=1}^{N} e_i\,. \tag{A-4}$$

Absolute average actual error,

$$\varepsilon_5 = \frac{1}{N}\sum_{i=1}^{N} \left|e_i\right|\,. \tag{A-5}$$

Standard deviation about average actual error,

$$\varepsilon_6 = \sqrt{\frac{\sum_{i=1}^{N}\left(e_i - \varepsilon_4\right)^2}{N-1}}\,. \tag{A-6}$$

In the above expressions, N is the total number of data points and $e_{r,i}$ and e_i, are the relative error and actual error, defined by:

$$e_{r,i} = \left.\frac{F_{E,Cal} - F_{E,Mea}}{F_{E,Mea}}\right|_i\,, \tag{A-7}$$

$$e_i = \left.F_{E,Cal} - F_{E,Mea}\right|_i\,. \tag{A-8}$$

Nomenclature

C = droplet concentration

D = pipe diameter

e = error

F_E = entrainment fraction

Fr = Froude number

K = simplified coefficient

k = entrainment and deposition coefficient

L = measurement distance from entrance

l = characteristic length

N = total number of data points

R = atomization and deposition rate

Re = Reynolds number

S_I = interfacial perimeter

S_I^* = ideally stratified interfacial perimeter

V = velocity

W = mass flow rate

We = Weber number

Greek Letters

δ = liquid film thickness

Γ = function indicator

Θ = pipe circumferential wetted fraction

μ = viscosity

θ = pipe inclination angle

ρ = density

σ = surface tension

τ = shear stress

ψ = coefficient in the entrainment model

Subscripts

A = atomization

C = gas core

c = critical

D = deposition

d = droplet

E = entrainment

F = liquid film

G = gas phase

I = interface

L = liquid phase

max = maximum

SG = superficial gas

SL = superficial liquid

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Table 1. Databank of Entrainment Fraction for Vertical Annular Flow.

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 2. Databank of Entrainment Fraction for Horizontal and Inclined 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. (1996)	0.026	0 ~ 75	Air/Water	60
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 3. Error Analysis Statistic Parameters for Entrainment Prediction Models.

Orientation	Model	ε_1	ε_2	ε_3	ε_4	ε_5	ε_6
Vertical	Chen (2005)	0.124	0.331	0.673	-0.005	0.087	0.109
	Oliemans (1986)	0.195	0.336	0.695	0.019	0.081	0.101
Horizontal	Chen (2005)	0.398	0.464	0.778	0.062	0.094	0.109
	Paleev and Filipovich (1966)	1.48	1.59	4.51	11.8	0.165	0.209
Inclined	Chen (2005)	0.475	0.682	1.08	0.014	0.067	0.083
	Equation 24	0.003	0.315	0.789	-0.043	0.054	0.091

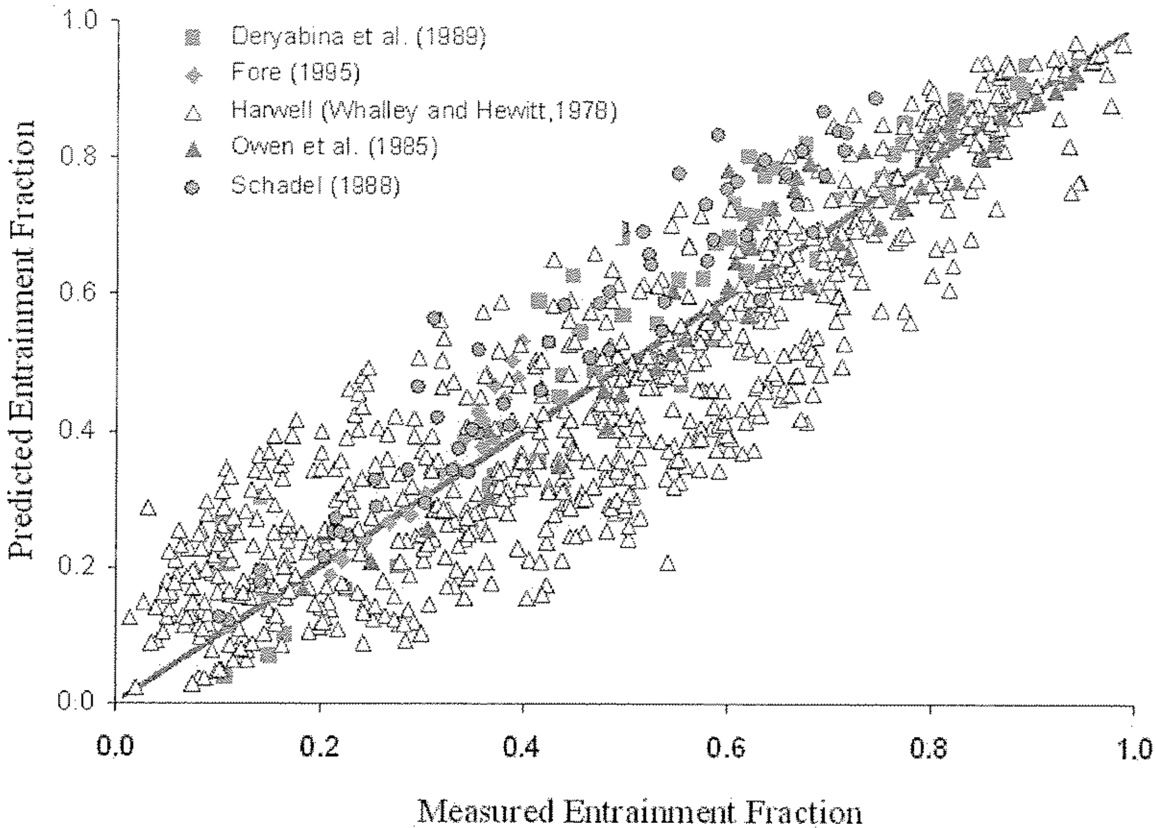


Figure 1. Predicted vs Measured Entrainment Fraction for Vertical Annular Flow by Chen Model.

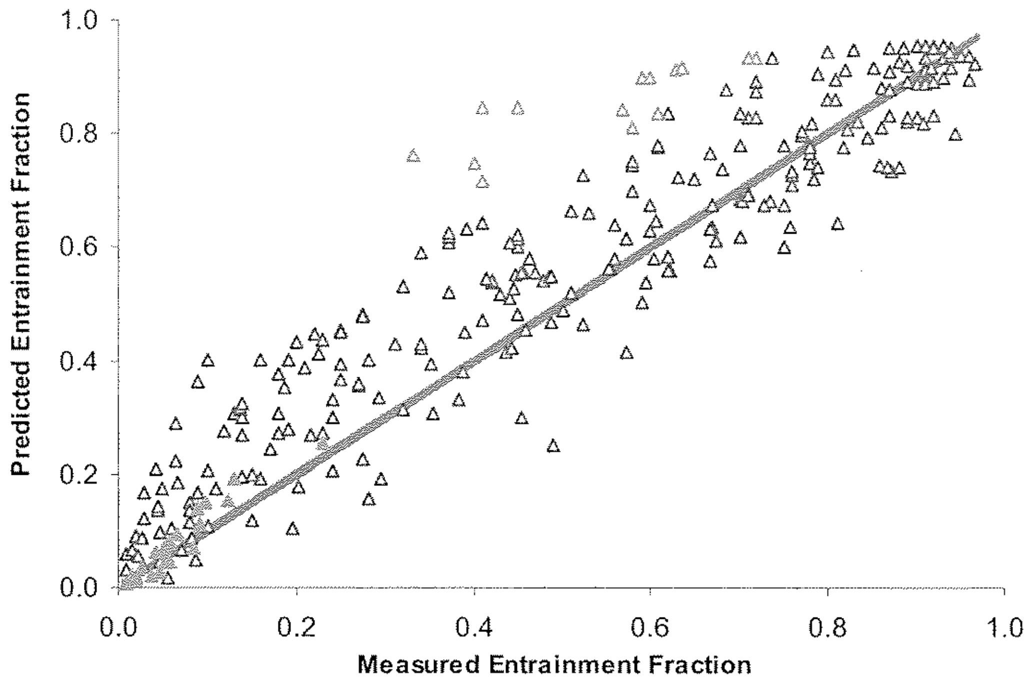


Figure 2. Predicted vs Measured Entrainment Fraction for Horizontal Stratified and Annular Flow by Chen Model.

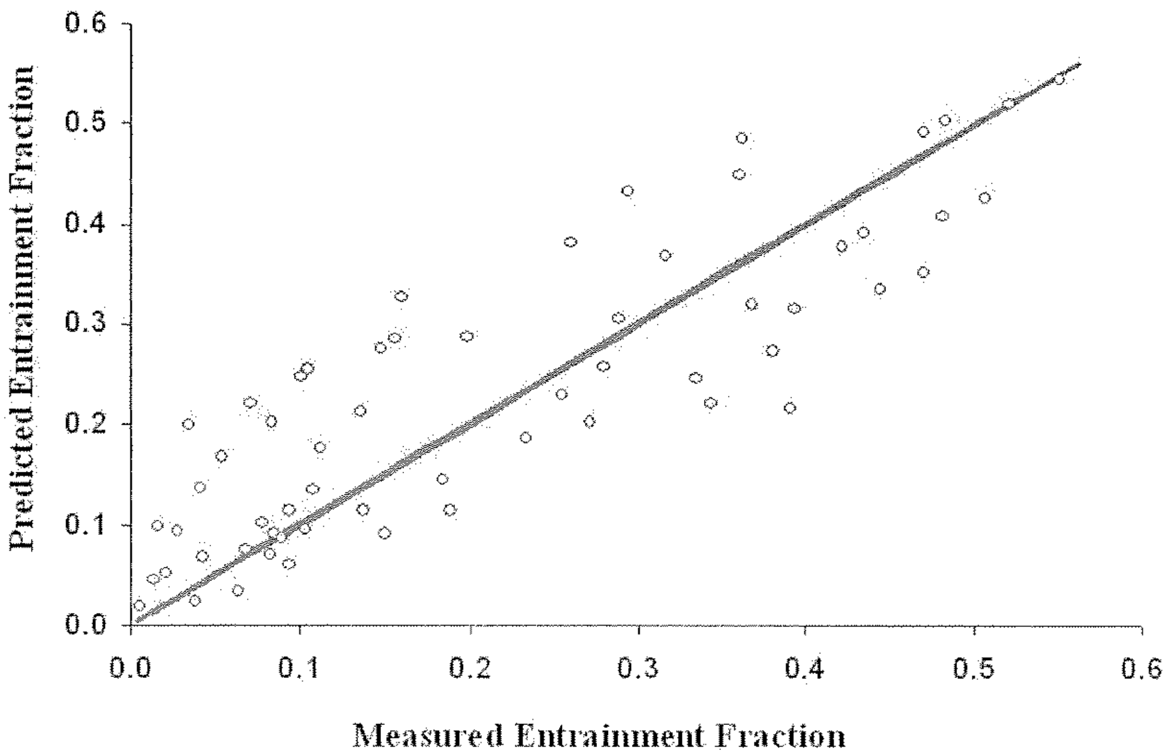


Figure 3. Predicted vs Measured Entrainment Fraction of Inclined Flow by Present Model.

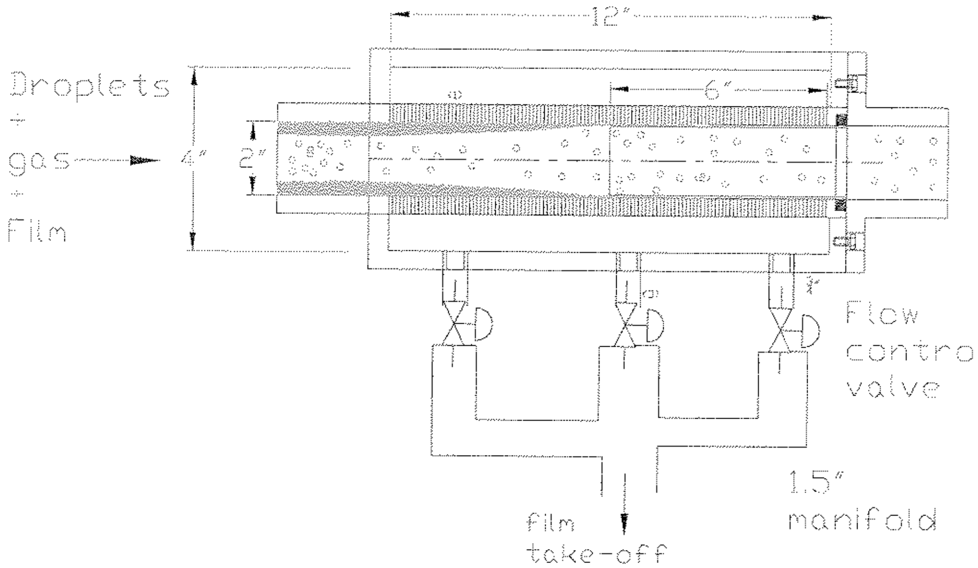


Figure 3. Entrainment measurement test section

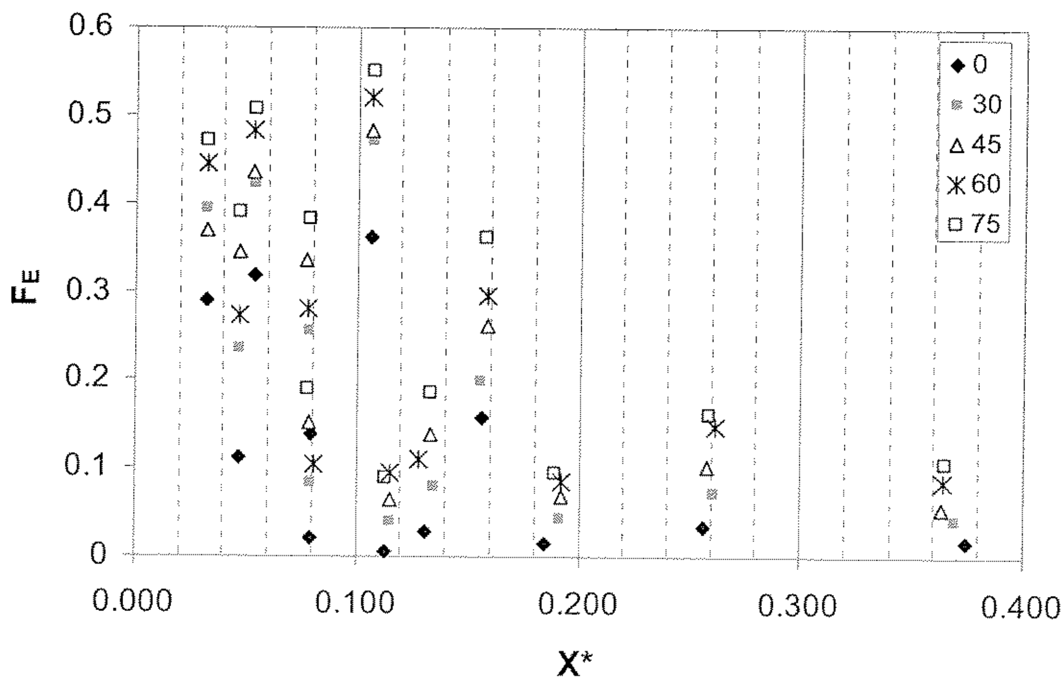


Figure 4. Entrainment fraction at different angles (Data of Ousaka et al. 1996)

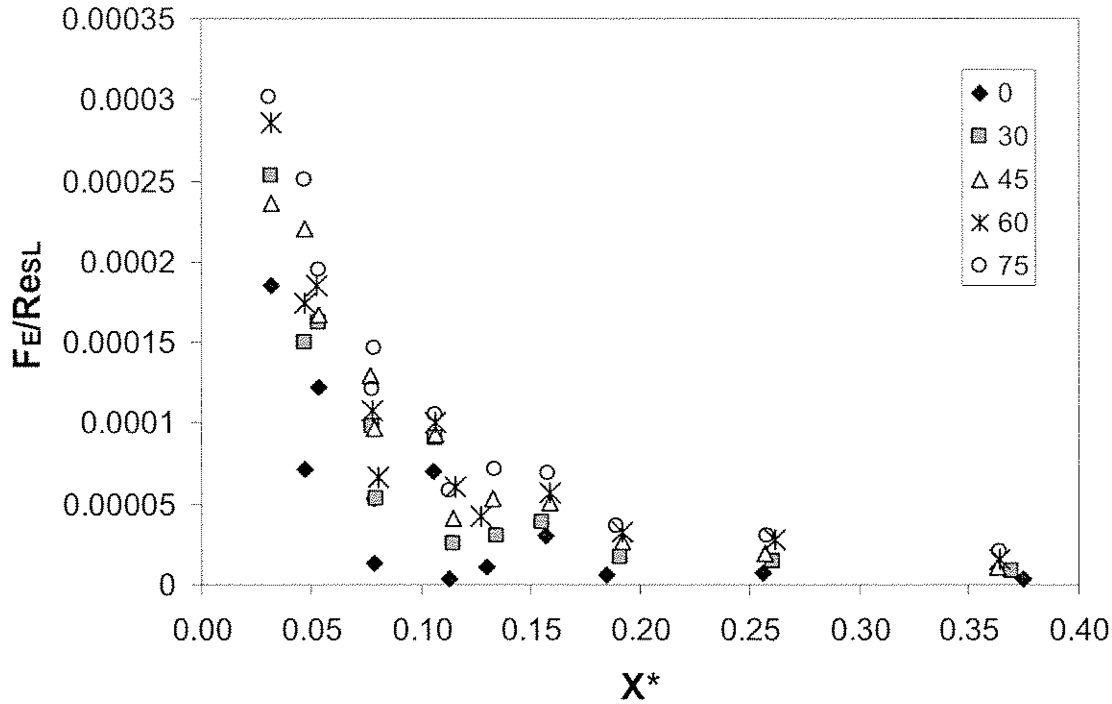


Figure 5. Entrainment fraction at different angles (Data of Ousaka et al. 1996)

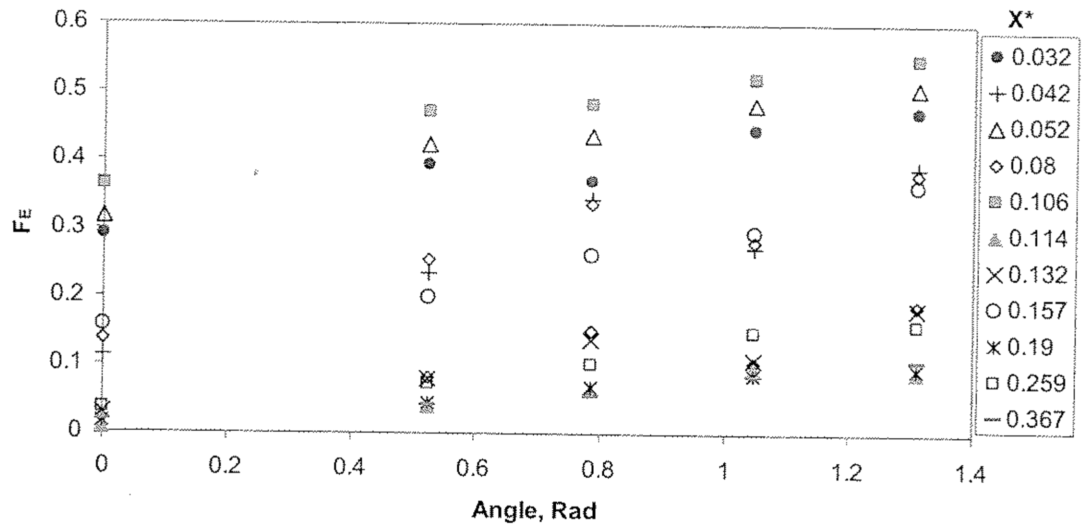


Figure 6. Entrainment fraction at different angles (Data of Ousaka et al. 1996)

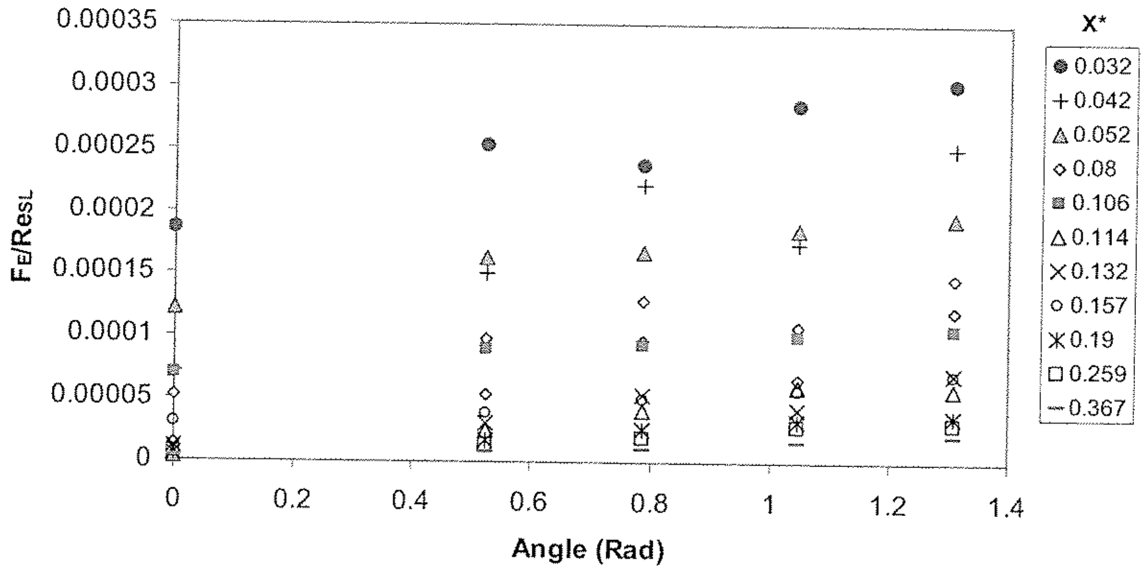


Figure 7. Normalized entrainment fraction at different angles (Data of Ousaka et al. 1996)

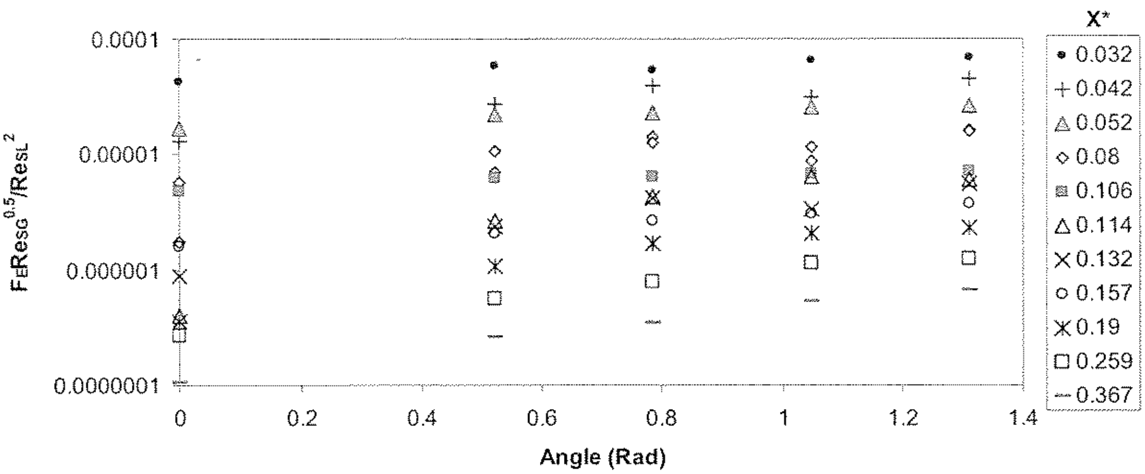


Figure 8. Normalized entrainment fraction at different angles (Data of Ousaka et al. 1996)

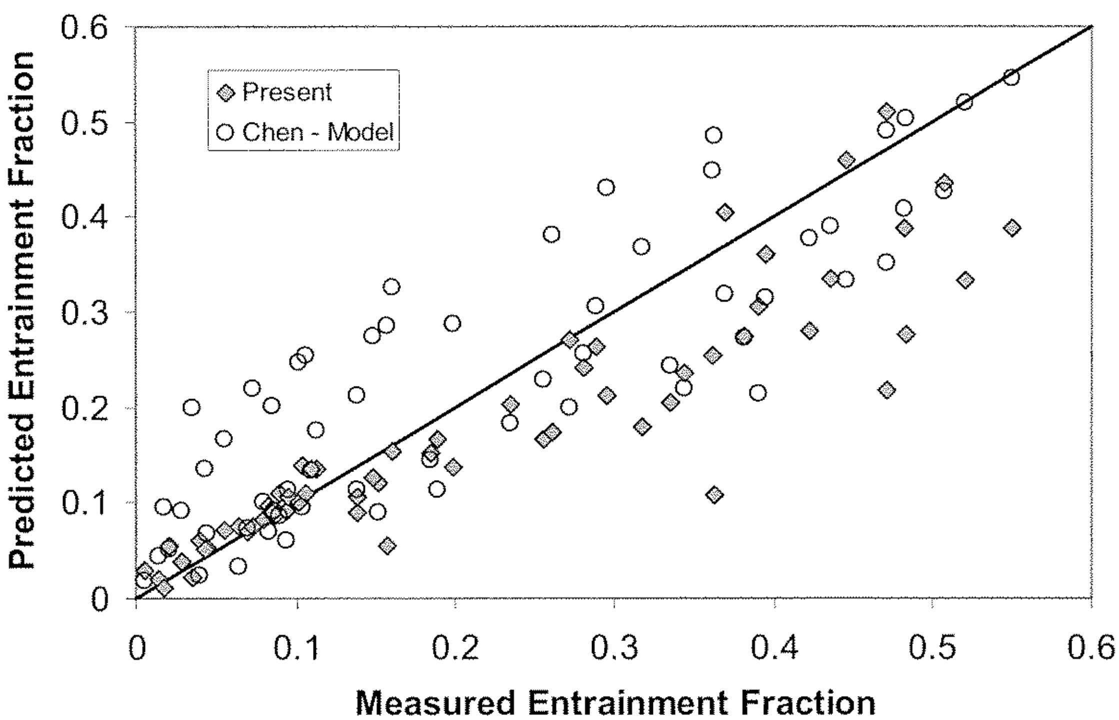


Figure 9. Predicted vs. Measured Entrainment Fraction (Based on the inclined data from Ousaka 1996 experiment)

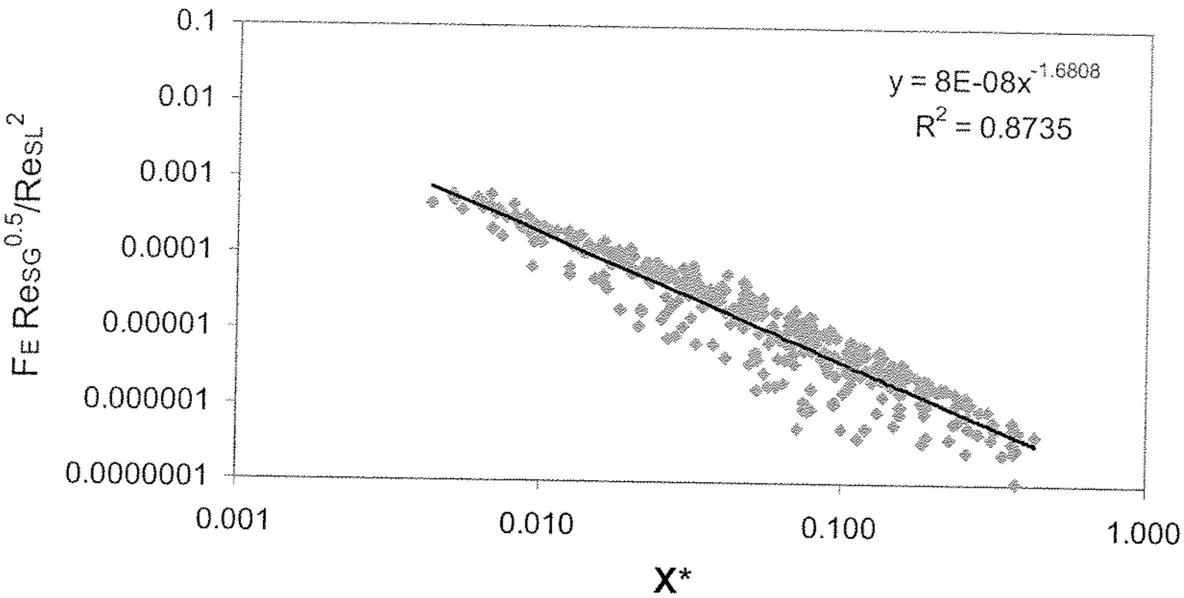


Figure 10 A. Entrainment fraction vs. X^* of all data points (Horizontal, Inclined and Vertical pipes)

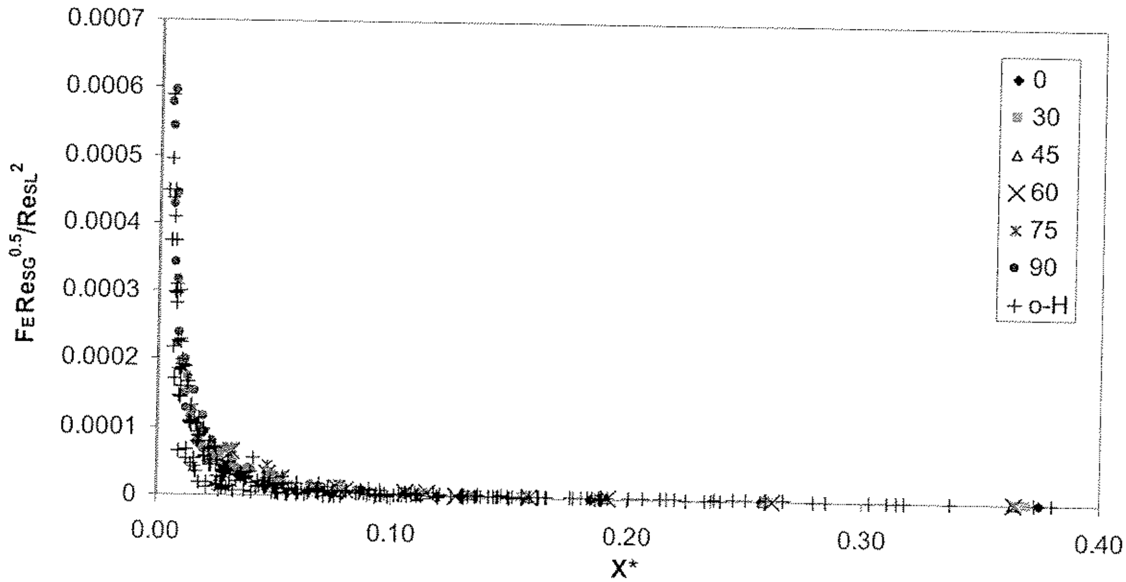


Figure 10 B. same as Figure 10 A but with linear scale

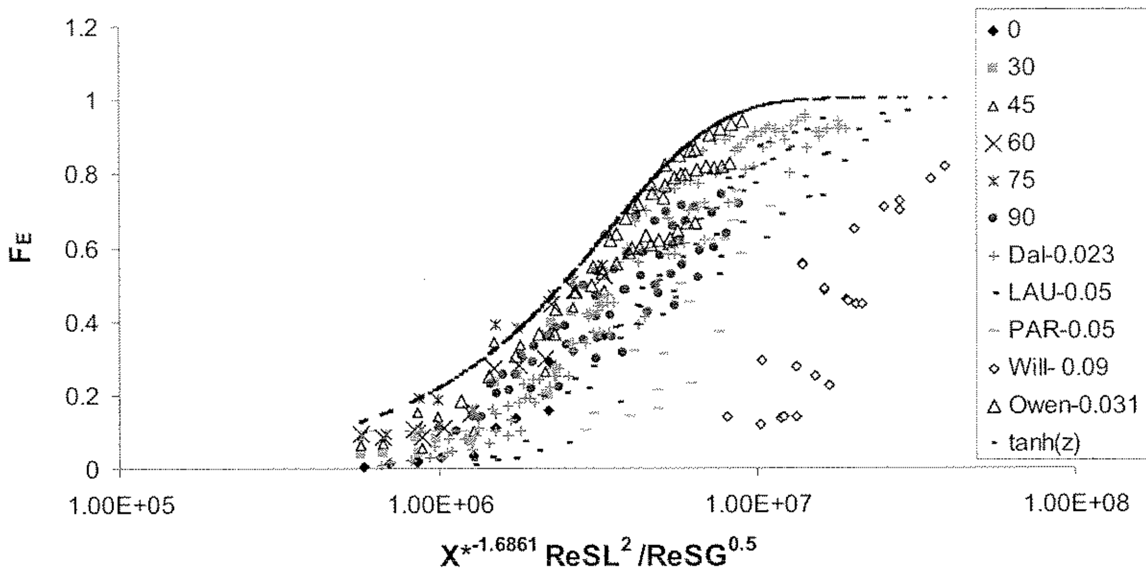


Figure 11. Entrainment fraction of all data points (Horizontal, Inclined and Vertical pipes)

$$z = 2.2\times10^{-7}\frac{X^{*-1.6861}\,\mathrm{Re}_{SL}^{2}}{\mathrm{Re}_{SG}^{0.5}}$$

Fluid Flow Projects

Up-scaling Studies in Multiphase Flow

Al-Sarkhi, Abdel

Advisory Board Meeting, November 6, 2007

Outline

- Objectives
- Introduction
- 6 in. Diameter High Pressure Facility
- 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

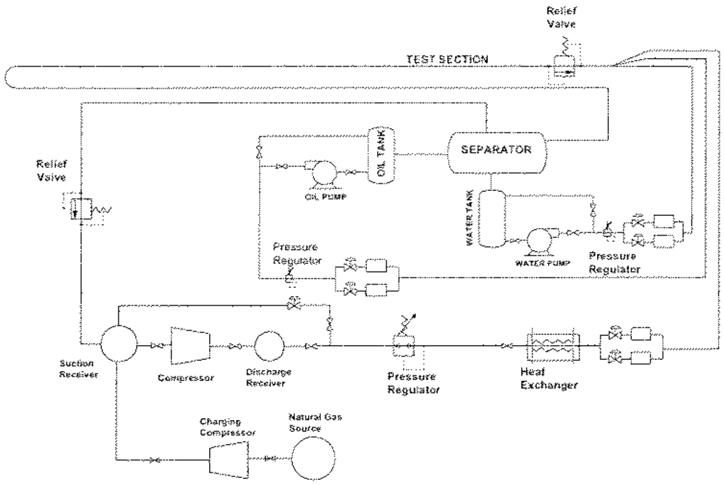
Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Introduction

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

Fluid Flow Projects Advisory Board Meeting, November 6, 2007

High Pressure Facility



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Fluids

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

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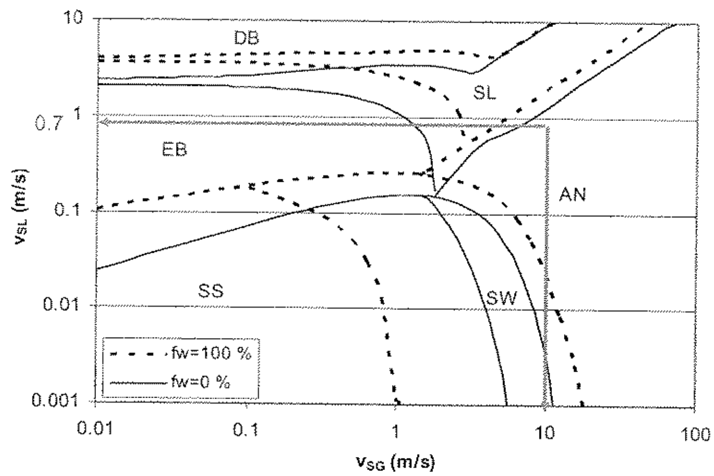
Flow Pattern Maps



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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

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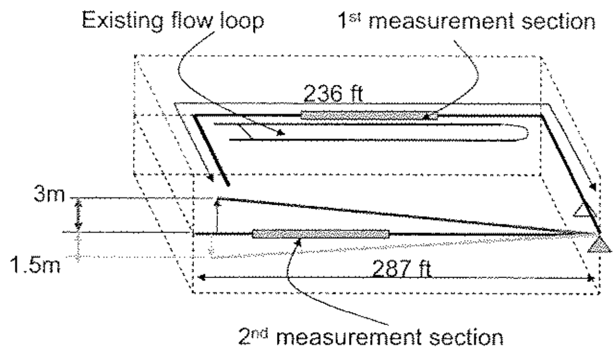
Test Section

Total Flow Loop Length = 523 ft = 160 m

Inclined Part Length = 287 ft = 87 m

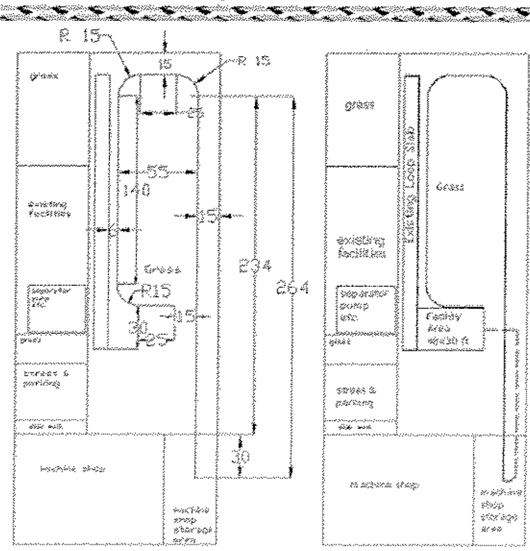
2° upward = 3 m

1° downward = 1.5 m



Large Bend
15 ft 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

Capital Cost Analysis

#	Component	Capacity	Cost (K $)
1	Compressor	18 MMSCFD	240
2	Heat Exchanger	720,000 BTU/HR/Pass	16
3	Chiller	60 ton	36
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	Test section	6-in. ID, 540 ft	20

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 Slab	600 ft by 6 ft	50
	Total		**714**

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Time Table

Tasks	Status	Completing time/ or required time
Quotation & Order	Under way	November 30, 2007
Engineering Design, Review		8-10 weeks
Equipment Manufacture		
Compressor	**Quote R.**	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	**Quote R.**	16 weeks
Construction		June 30, 2008
Calibration & Shake Down Tests		Nov. 30, 2008

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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

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Upscaling Studies in Multiphase Flow

Al-Sarkhi Abdel

Objectives

Scaling up of small diameter and low pressure results to the 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 be able 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 these experimental conditions. It is important to validate the applicability of the models with experimental results obtained for conditions similar to those experienced in the 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 the 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. The Tulsa City Natural gas is the gas phase. Tulco Tech-80 Mineral oil and Tulsa City water are the liquid phases.

Experimental Setup

The facility is composed of gas, oil, water system and separation systems and test section. The operating pressure will be 500 psig. The flow loop length will be 523 ft approximately. The last section will have the ability to be inclined 2° upward and 1° downward. 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 pipe will be 100 ft away from the pipe outlet which makes the L/D ratio on the inclinable section only (from starting point of the inclined section) around 374 to ensure a fully developed flow.

The 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. Fig. 1C shows the location and details of the inclinable part.

Operating Conditions Range

Flow pattern maps have been generated using Barnea model with two water cuts (0 % and 100%) for a 6 in. 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, the flow patterns will be mainly stratified flow and intermittent flow.

Gas, Oil, Water and Separation Systems

According to maximum gas and liquid superficial velocities, the capacities of 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 for compressor. The volume of 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 60" x 20'. The separator will have a pressure rating of 600 psig.

Heat Exchanger & Chiller

Based on the Sundyne compressor specification sheet for the inlet condition 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 the temperature of about 38 °F. A heat exchanger must be designed and installed to fix the gas temperature same as the inlet temperature (100 °F). Based on all parameters summarized in Table 3 for the natural gas (Methane), a heat exchanger with maximum (at maximum flow rate) heat duty of 210 KW (720,000 BTU/HR) is required. A chilled water must be provided to the heat exchanger. Based on the maximum operating condition, a 60 ton Chiller must be used.

Test section

The inner diameter of test section will be 6 in. A proposed design of the test section is shown in Fig. 1. With this design, the flow developing section will be longer than exiting test section. The inclination angle can be changed from -1 to 2 degree. Two measurement sections will be made. The first one at 135 ft and the second at 440 ft from the entrance which makes L/D to be 270 and 880, respectively. To minimize the effect of pipe bend, a very long bend with 15 ft radius will be installed.

Basic Instrumentation

Flow rates for gas, oil and water phase will be measured by Micro Motion flow meters separately. 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.

Using quick closing valves to measure the liquid hold up in high pressure system, a trapped liquid measurement vessel needs to be design to measure the volume of the trapped liquid.

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

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 are being shopped around and negotiated with suppliers. The estimated costs for the three phase facilities are listed in Table 1. Labor cost is not included.

Time Table

The completion of the design and construction of the facility is expected to be ready to operate by November 2008 (see Table 2). The most time consuming item is the Compressor. Once the compressor is ordered, it takes about 6-8 months to receive the delivery.

Proposed Initial Project

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

Table 1. Facility Capital Cost Analysis (in $1000)

	Component	Capacity	Cost	Status
1	Compressor	18 MMSCFD	240	Q. R.
2	Heat Exchanger	720,000 BTU/HR/pass	16	Q. R.
3	Chiller	60 ton	36	Q. R.
4	Safety Valves	2	2	
5	Water Pump	200 GPM	20	Q.U.
6	Oil Pump	200 GPM	20	Q.U.
7	Separator	54" x 10' @ 600 psig	36	Q. R.
8	Water Tank	1200 gallon	33	Q. R.
9	Oil Tank	1200 gallon	33	Q. R.
10	Test Section	6 in. ID, 540 ft	20	
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 (5)	10	
18	Power Generator	500 KW	65	Q. R.
19	Steel structure/Tilting		50	
20	Pressure Regulator	3 (oil, water & gas)	5	
21	Concrete Slab	600 ft by 5 ft	50	Q.U.
	Total		$ 714K	

Q. R.: Qoute Received ; Q. U.: Qoute Underway.

Table 2: Time Table for Facility Construction

Tasks	Status	Completing Time/ or required time
Quotation & order	Under way	November 30, 2007
Engineering design, review		8-10 weeks
Equipment manufacture		
Compressor	Q. R.	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	Q. R.	16 weeks
Construction		June 30, 2008
Calibration & shake down tests		Nov. 30, 2008

Table 3: Methane properties and flow conditions for Heat Exchanger design

Methane 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
Methane critical point temperatue, Tc	343.9 R	191.1 K
Methane 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 Methane 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

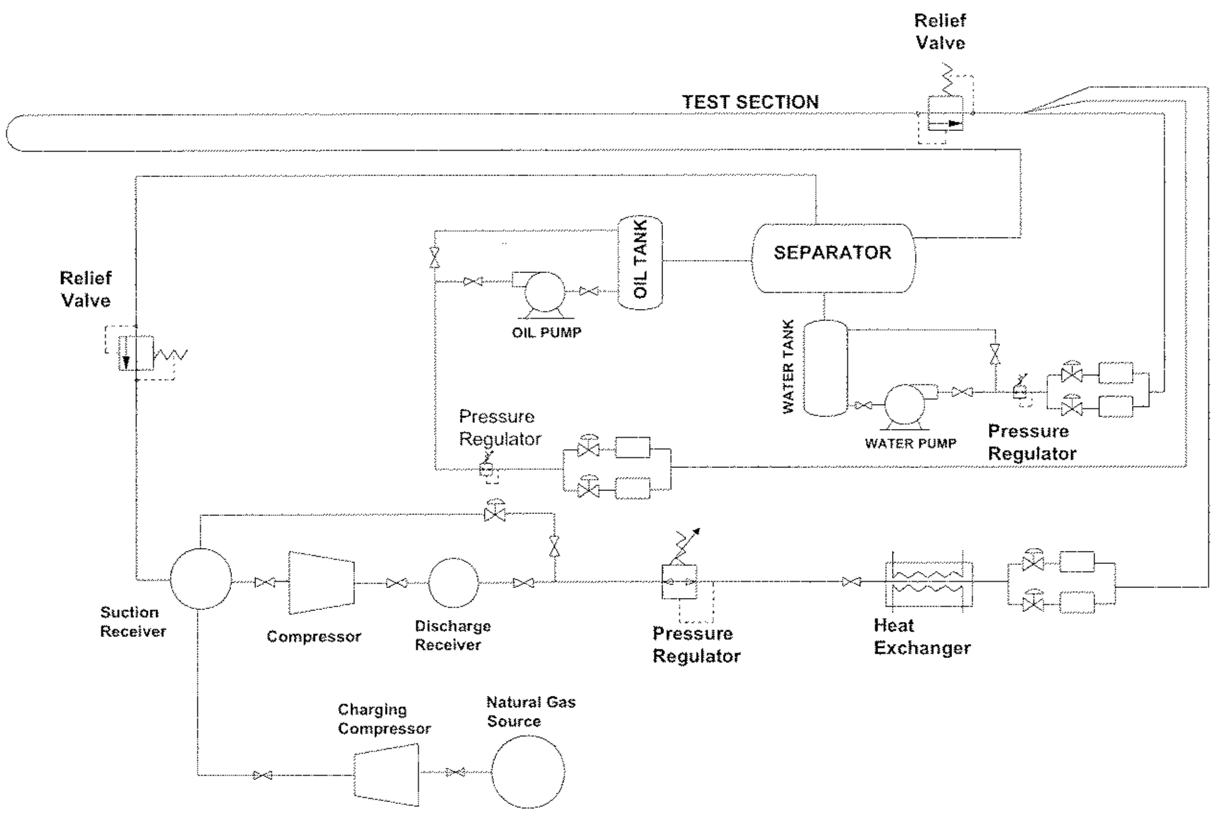

Figure 1A. Schematic of high pressure facility

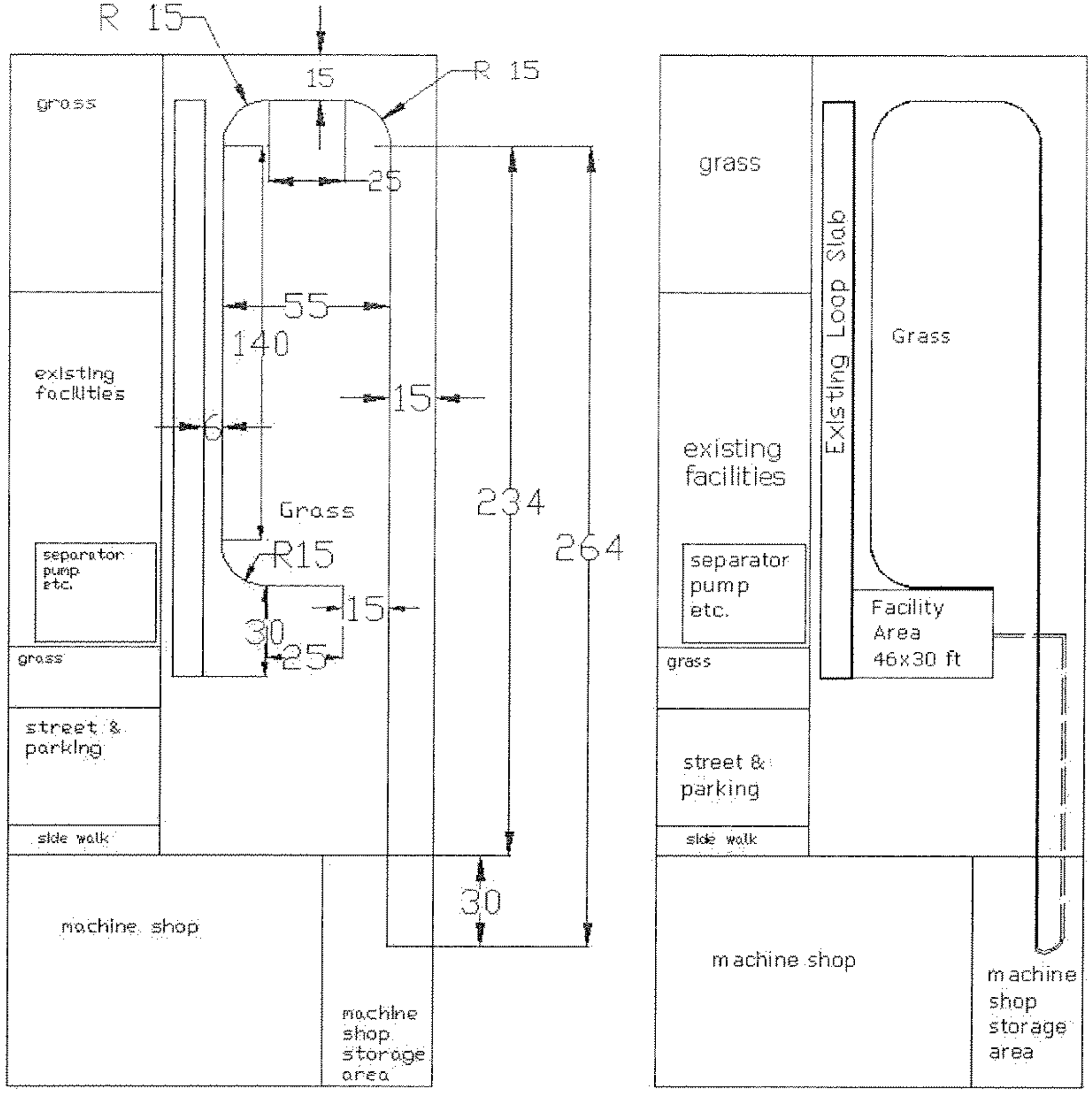

Figure 1B: Flow loop layout and the available space (dimensions are in feet)

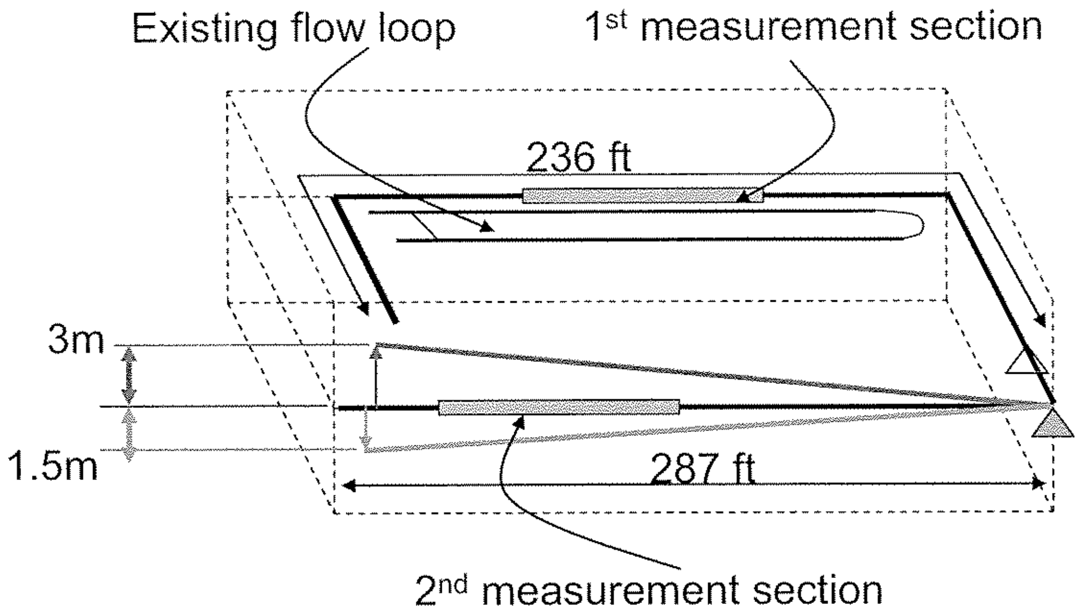

Figure 1C: Pipe inclination details

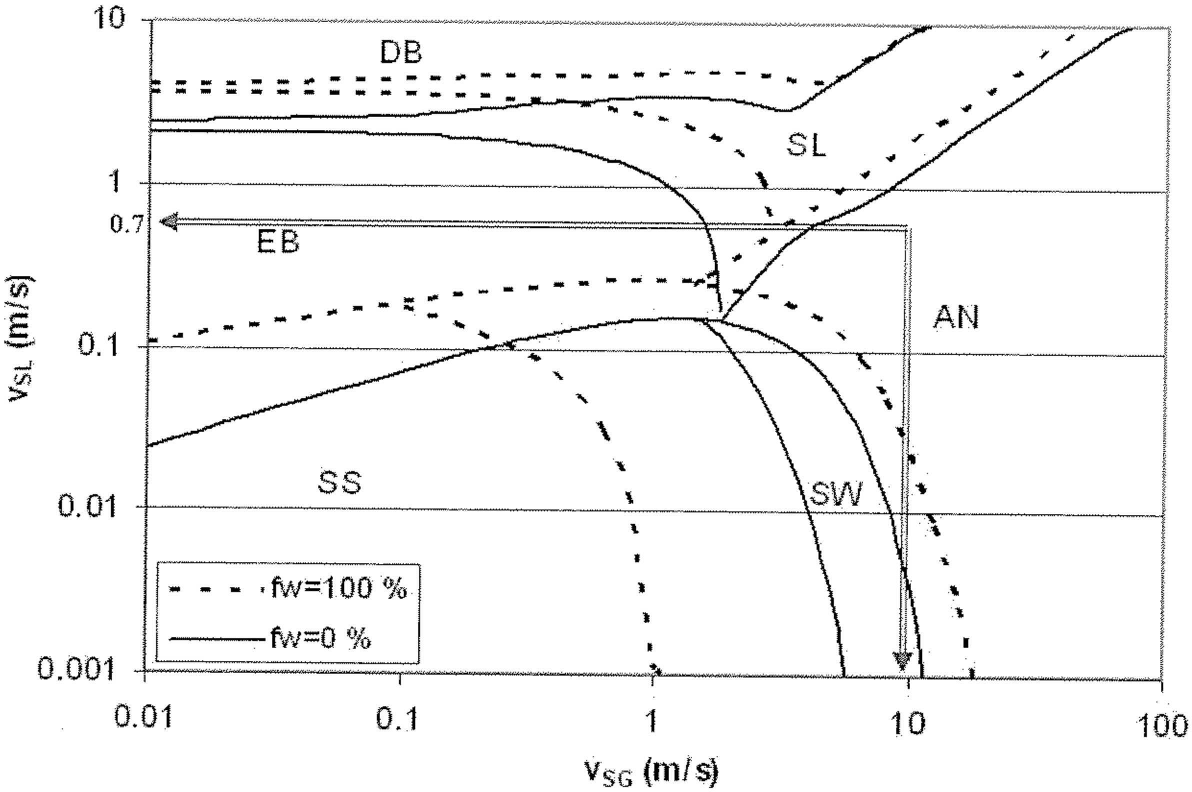

Figure 2. Flow pattern map for 100% and 0% water cut at 500 psig, 6 in. pipe

Fluid Flow Projects

Unified Model and Computer Program Updates

Holden Zhang

Advisory Board Meeting, November 6th, 2007

Outline

- Objectives
- Unified Model Testing
- TUFFPT – Demo
- Documentation
- Future Plan

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

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Unified Model Testing

- Two-Phase Unified Model is being Incorporated into Schlumberger PIPEsim
- Fortran Codes Updated to PIPEsim Programming Standards
  - Two-Phase
  - Three-Phase
- Many Communications with PIPEsim Engine Developers
- Improved Program Convergence

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Unified 2-P 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

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Unified 2-P Model Harness Tests ...

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

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Unified Model Testing

- Same Harness Tests Planned for 3-P Unified Model
- Putting together 2-P and 3-P Databanks for Model Verifications
  - TUFFP Well Databank
  - TUFFP Pipeline Databank
  - Data Collected from Literature
  - Recent New Data

TUFFPT – Demo

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

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TUFFPT …

- Flow Pattern
  - Gas-Liquid Pipe Flow Pattern Maps Predicted by Different Mechanistic Models – Taitel & Dukler, Barnea and TUFFP Unified

TUFFPT …

- Case Study
  - Show Multiphase Flow Change with Any Input Parameter
  - Compare Model Predictions with Lab or Field Data

TUFFPT ...

- Contour Plot
  - Multiphase Flow Behaviors Visualized on 2-D Map against Gas and Liquid Flow Rate Changes
  - Easy to Find Abnormal Points or Areas

TUFFPT ...

- Pipeline
  - Hydrodynamic and Thermal Calculations of Multiphase Flow along a Pipeline or Well
  - With or without Heat Transfer

Standard I/O Format

- Will be Used for All within TUFFP for
  - Experimental Data Collections
  - Comparisons with Model Predictions

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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Future Plan

- Verifications of 2-P and 3-P Models with Databanks
- Improve TUFFPT
- Continuously Improve Closure Relationships in Unified Models

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Fluid Flow Projects

2007 Questionnaire - Results

Al-Sarkhi Abdel

Advisory Board Meeting, November 5, 2007

2007 Questionnaire Results

#	Research Title	Status	Baker Atlas	BP	Chevron	ConocoPhillips	ExxonMobils	JOGMEC	Kuwait Oil Co.	Landmark	Marathon	MMS	Pemex	Petrobras	Petronas	Rosneft	Schlumberger	Shell	Tenaris	Total	Total Scores	Priority Ranking
1	Gas-Oil-Water Flow in Pipes	O	5	5	5	5	2	5	4	5	5	4		3	5	3	5	4	5	5	75	1
2	Oil-Water Flow	O	4	4	5	5	2	4	5	2	5	4		3	5	3	4	3	3	5	66	4
3	Unified Modeling of Multiphase Pipe Flows (Including Gas-Liquid, Oil-Water and Gas-Oil-Water Flows)	O	5	3	4	5	1	2	3	3	5	5		4	4	5	5	3	3	5	65	5
4	Multiphase Flow in Hilly Terrain Pipelines	O	5	3	4	4	1	4	3	2	3	3		3	3	2	2	2	4	5	53	9
5	Effect of High Viscosity on Multiphase Flow Behavior	O	4	4	5	4	3	5	5	2	4	3		5	5	2	5	5	3	5	69	3
6	Closure Laws for Droplet-Homophase Interaction	O	4	2	5	5	2	2	2	2	2	2		4	3	2	3	4	3	5	52	10
7	Three-Phase Flow in Near-Horizontal Pipelines with Low Oil-Water Loadings	O	4	2	4	5	5	5	5	2	2	4		4	3	2	3	4	4	5	63	6

Ranks: 5 – Very High; 4 – High; 3 – Med; 2 – Low; 1 – None

Status: O – Ongoing; P – Potential; S – Scheduled

Fluid Flow Projects

Advisory Board Meeting, November 5, 2007

2007 Questionnaire Results

#	Research Title	Status	Baker Atlas	BP	Chevron	ConocoPhillips	ExxonMobils	JOGMEC	Kuwait Oil Co.	Landmark	Marathon	MMS	Pemex	Petrobras	Peronas	Rosneft	Schlumberger	Shell	Tenaris	Total	Total Scores	Priority Ranking
8	Lagrangian-Eulerian Transient Two-Phase Flow Model	O	4	2	2	4	1	3	1	2	2	2		3	2	5	5	2	1	5	46	14
9	Up-scaling Studies in Multiphase Flow	O	5	5	5	4	5	5	3	3	4	4		5	4	5	4	5	3	5	74	2
10	Two-Phase Downward Flow and Gas Carryunder	P	3	3	4	2	3	5	1	2	5	3		2	5	2	2	3	3	5	53	9
11	Closure Relationship Study and Numerical Simulation of Slug Flow	P	5	3	4	4	1	5	4	3	2	2		4	3	3	3	2	4	5	57	8
12	Effect of Wave Characteristics on Interfacial Shear Stress	P	4	2	4	4	4	4	1	2	2	3		3	2	2	2	3	2	5	49	12
13	Investigation of Four-Phase Solid, Water, Oil and Gas Flow	P	4	4	4	5	3	4	3	5	2	3		2	5	5	2	5	5	5	66	4

Ranks: 5 – Very High; 4 – High; 3 – Med; 2 – Low; 1 – None   Status: O – Ongoing; P – Potential; S – Scheduled

Fluid Flow Projects   Advisory Board Meeting, November 5, 2007

2007 Questionnaire Results

#	Research Title	Status	Baker Atlas	BP	Chevron	ConocoPhillips	ExxonMobils	JOGMEC	Kuwait Oil Co.	Landmark	Marathon	MMS	Pemex	Petrobras	Peronas	Rosneft	Schlumberger	Shell	Tenaris	Total	Total Scores	Priority Ranking
14	Gas-Liquid Flow in Undulating Horizontal Wells	P	5	3	3	2	1	5	2	3	2	4		3	2	4	4	2	4	2	51	11
15	Investigation of Inversion Point in Oil-Water Flow	P	4	2	4	3	2	5	3	2	2	4		2	4	4	5	4	5	5	60	7
16	Two-Phase Flow in Coiled Tubing	P	2	2	2	2	1	4	2	5	2	2		2	2	3	2	2	3	2	40	15
17	Effect of Drag-Reducing Polymers on Gas-Oil-Water Pipe Flow	P	3	2	3	5	4	2	1	4	2	4		4	4	2	3	2	4	2	51	11
18	Effect of Drag-Reducing Polymers on Oil-Water Flow in Pipes	P	3	2	3	5	3	2	1	3	2	3		2	4	2	3	2	4	2	46	14
19	Investigation of Gas Well Unloading	P	3	3	2	2	2	5	3	1	5	2		2	3	3	5	3	3	2	49	12
20	Investigation of Tubular Tool-Joint Effects on Multiphase Flows	P	3	3	4	2	2	3	2	5	2	2		2	2	2	2	4	5	2	47	13

Ranks: 5 – Very High; 4 – High; 3 – Med; 2 – Low; 1 – None   Status: O – Ongoing; P – Potential; S – Scheduled

Fluid Flow Projects   Advisory Board Meeting, November 5, 2007

Top 10 Projects

#	Research Title		Score	Rank 2007	Rank 2006
1	Gas-Oil-Water Flow in Pipes	O	75	1 ⇧	2
9	Up-scaling Studies in Multiphase Flow	O	74	2 ⇧	3
5	Effect of High Viscosity on Multiphase Flow Behavior	O	69	3 ⇩	1
2	Oil-Water Flow	O	66	4 ⇩	3
13	Investigation of Four-Phase Solid, Water, Oil and Gas Flow	P	66	4 ⇧	8
3	Unified Modeling of Multiphase Flows (Including Gas-Liquid, Oil-Water, Gas-Oil-Water Flows)	O	65	5 ⇩	1
7	Three-Phase Flow in Near Horizontal Pipelines with Low Oil-Water Loading	O	63	6 ⇩	5
15	Investigation of Inversion Point in Oil-Water Flow	P	60	7 ⇩	5
11	Closure Relationship Study and Numerical Simulation of Slug Flow	P	57	8 ⇩	7
4	Multiphase Flow in Hilly Terrain Pipelines	O	53	9 ⇩	5

Fluid Flow Projects Advisory Board Meeting, November 5, 2007

Questionnaire 2007

Comments

&

Suggestions

Fluid Flow Projects Advisory Board Meeting, November 5, 2007

2007 Questionnaire Results

#	Research Title	Status	Baker Atlas	BP	Chevron	ConocoPhillips	ExxonMobils	JOGMEC	Kuwait Oil Co.	Landmark	Marathon	MMS	Pemex	Petrobras	Peronas	Rosneft	Schlumberger	Shell	Tenaris	Total	Total Scores	Priority Ranking
1	Gas-Oil-Water Flow in Pipes	O	5	5	5	5	2	5	4	5	5	4		3	5	3	5	4	5	5	75	1
2	Oil-Water Flow	O	4	4	5	5	2	4	5	2	5	4		3	5	3	4	3	3	5	66	4
3	Unified Modeling of Multiphase Pipe Flows (Including Gas-Liquid, Oil-Water and Gas-Oil-Water Flows)	O	5	3	4	5	1	2	3	3	5	5		4	4	5	5	3	3	5	65	5
4	Multiphase Flow in Hilly Terrain Pipelines	O	5	3	4	4	1	4	3	2	3	3		3	3	2	2	2	4	5	53	9
5	Effect of High Viscosity on Multiphase Flow Behavior	O	4	4	5	4	3	5	5	2	4	3		5	5	2	5	5	3	5	69	3
6	Closure Laws for Droplet-Homophase Interaction	O	4	2	5	5	2	2	2	2	2	2		4	3	2	3	4	3	5	52	10
7	Three-Phase Flow in Near-Horizontal Pipelines with Low Oil-Water Loadings	O	4	2	4	5	5	5	5	2	2	4		4	3	2	3	4	4	5	63	6
8	Lagrangian-Eulerian Transient Two-Phase Flow Model	O	4	2	2	4	1	3	1	2	2	2		3	2	5	5	2	1	5	46	14
9	Up-scaling Studies in Multiphase Flow	O	5	5	5	4	5	5	3	3	4	4		5	4	5	4	5	3	5	74	2
10	Two-Phase Downward Flow and Gas Carryunder	P	3	3	4	2	3	5	1	2	5	3		2	5	2	2	3	3	5	53	9
11	Closure Relationship Study and Numerical Simulation of Slug Flow	P	5	3	4	4	1	5	4	3	2	2		4	3	3	3	2	4	5	57	8
12	Effect of Wave Characteristics on Interfacial Shear Stress	P	4	2	4	4	4	4	1	2	2	3		3	2	2	2	3	2	5	49	12
13	Investigation of Four-Phase Solid, Water, Oil and Gas Flow	P	4	4	4	5	3	4	3	5	2	3		2	5	5	2	5	5	5	66	4
14	Gas-Liquid Flow in Undulating Horizontal Wells	P	5	3	3	2	1	5	2	3	2	4		3	2	4	4	2	4	2	51	11
15	Investigation of Inversion Point in Oil-Water Flow	P	4	2	4	3	2	5	3	2	2	4		2	4	4	5	4	5	5	60	7
16	Two-Phase Flow in Coiled Tubing	P	2	2	2	2	1	4	2	5	2	2		2	2	3	2	2	3	2	40	15
17	Effect of Drag-Reducing Polymers on Gas-Oil-Water Pipe Flow	P	3	2	3	5	4	2	1	4	2	4		4	4	2	3	2	4	2	51	11
18	Effect of Drag-Reducing Polymers on Oil-Water Flow in Pipes	P	3	2	3	5	3	2	1	3	2	3		2	4	2	3	2	4	2	46	14
19	Investigation of Gas Well Unloading	P	3	3	2	2	2	5	3	1	5	2		2	3	3	5	3	3	2	49	12
20	Investigation of Tubular Tool-Joint Effects on Multiphase Flows	P	3	3	4	2	2	3	2	5	2	2		2	2	2	2	4	5	2	47	13

5 - Very High
4 - High
3 - Med
2 - Low
1 - None

O - Ongoing
P - Potential
S - Scheduled

Fluid Flow Projects

Business Report

Cem Sarica

Advisory Board Meeting, November 6, 2007

Membership Status

- Current Status
  - Membership Stands at 18
    - 17 Industrial and MMS
    - ExxonMobil and JOGMEC Joined
  - Efforts Continue to Increase Membership
    - BHP and Saudi Aramco Indicated Their Interest

Membership Status …

- DOE Support
  - Started June 2003
  - $731,995 Over Five Years
  - Gas-Oil-Water Flow Research
    - Development of Next Generation Multiphase Prediction Tools

Fluid Flow Projects Advisory Board Meeting, November 6, 2007

$48K

Personnel Changes

- Dr. Qian Wang Accepted a Position with ScandPower
  - Effective June 25
  - Served as Post Doctoral Research Associate Over Six Years

Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Personnel Changes …

- New Additions to Our Team
  - Dr. Abdel Salam Al-Sarkhi
    - New Research Associate of TUFFP
    - Joined in June 2007
    - Associate Professor of Mechanical Engineering at Hashemite University, Jordan
    - Ph.D. from Oklahoma State
    - Post Doctoral Research Experience under Professor Thomas J. Hanratty
    - Experience in Multiphase Flow

Personnel Changes …

- New Additions to Our Team …
  - Dr. Mingxiu (Michelle) Li
    - Ph.D. in Bio-Fluid Dynamics from the University of Edinburgh–Department of Mechanical Engineering in March 2007
    - M. Phil in Engineering Thermophysics from Department of Energy and Power Engineering of Xia'tong University in China
    - Currently assigned to TUCoRE and TUFFP projects

Conferences

- SPE 2007 Annual Technical Conference & Exhibition
  - Anaheim, CA, Nov. 11 – 14, 2007
  - Two Papers from TUFFP Research Projects
    - SPE 109591, Vielma, M., Atmaca, S., Zhang, H. Q., and Sarica, C.: "Characterization of Oil/Water Flows in Horizontal Pipes"
    - SPE 110221, Keskin, C., Zhang, H. Q., and Sarica, C.: "Identification and Classification of New Three-Phase Gas/Oil/Water Flow Patterns"

Next Advisory Board Meetings

- Tentative Schedule
  - March – date to be determined – to follow DeepStar meeting
    - TUHFP Meeting
  - April 21, 2008
    - TUHOP Meeting
    - TUFFP Workshop
    - Facility Tour
    - TUHOP/TUFFP Social Function
  - April 22, 2008
    - TUFFP Meeting
    - TUFFP/TUPDP Reception
  - April 23, 2008
    - TUPDP Meeting
- ACAC, TU South Campus

Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Financial Report

- Year 2007 Summary
  - TUFFP Industrial Account
  - TUFFP MMS Account
  - TUFFP DOE Account
- Year 2008 Proposed
  - TUFFP Industrial Account
  - TUFFP MMS Account
  - TUFFP DOE Account

Fluid Flow Projects | Advisory Board Meeting, November 6, 2007

2007 TUFFP Industrial Account Budget Summary
(Prepared October 22, 2007)

Reserve Fund Balance on January 1, 2007		$644,242.26
Income for 2007		
	2007 Membership Fees (15 @ $40,000 - excludes MMS)	$600,000.00
	2007 Membership Fees (1 @ 30,000)	$30,000.00
	2007 Membership Fees (1 @ 50,000)	$50,000.00
Total Budget		$1,324,242.26

Projected Budget/Expenditures for 2007

		Budget	Expenses 10/22/07	Anticipated 2007 Expenses
90101 - 90110	Faculty Salaries	52,698.00	41,164.59	43,726.37
90600 - 90609	Professional Salaries	61,372.00	51,323.00	58,873.70
90700 - 90800	Technician - Miller	35,650.00	30,403.56	36,752.74
91000	Graduate Students - Monthly	50,100.00	41,939.61	46,584.67
91100	Students - Hourly	15,000.00	18,768.68	22,000.00
91800	Fringe Benefits (35%)	50,910.83	39,063.68	46,584.67
93100	General Supplies	3,000.00	3,355.43	4,000.00
93101	Research Supplies	100,000.00	71,012.77	85,000.00
93102	Copier/Printer Supplies	500.00	162.84	250.00
93104	Computer Software	4,000.00	924.39	1,000.00
93106	Office Supplies	2,000.00	755.40	1,000.00
93200	Postage/Shipping	500.00	1,489.75	1,500.00
93300	Printing/Duplicating	2,000.00	1,624.69	2,200.00
93400	Telecommunications	3,000.00	1,693.59	2,000.00
93500	Membership/Subscriptions	1,000.00	384.00	500.00
93600	Travel		153.81	153.81
93601	Travel - Domestic	14,000.00	4,562.72	10,000.00
93602	Travel - Foreign	10,000.00	2,662.83	3,662.83
93606	Visa		-	
93700	Entertainment (Advisory Board Meetings)	10,000.00	4,951.06	10,000.00
94803	Consultants		7,708.35	10,791.69
94813	Outside Services	20,000.00	7,076.11	10,000.00
95700	F&A (55.6%)	119,456.33	102,081.29	115,613.24
98961	Employee Recruiting	3,000.00		4,000.00
99001	Equipment	600,000.00	2,904.41	482,000.00
99002	Computers	8,000.00	17,309.66	20,000.00
99300	Bank Charges	40.00	18.00	18.00
81801	Tuition/Fees	30,306.00	34,250.00	34,250.00
81806	Graduate Fellowship		519.71	934.39
	Total Expenditures	$1,196,563.16	$488,133.83	$1,052,496.11

Anticipated Reserve Fund Balance on December 31, 2007 $ 271,746.15

2007 MMS Account Summary

(Prepared October 25, 2007)

Reserve Balance as of 12/31/06				$6,109.94
2007 Budget				$40,000.00
Total Budget				$46,109.94
Projected Budget/Expenditures for 2006				
		Budget	2007 Anticipated 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 12/31/06		$39,833.60	$40,788.00	
Total Anticipated Reserve Fund Balance as of 12/31/07				$5,321.94

Fluid Flow Projects

Advisory Board Meeting, November 6, 2007

2007 DOE Account Summary

(Prepared October 24, 2007)

Award Amount				$731,995.00
Amount Invoiced (June 1, 2003 - December 31, 2006)				$495,393.17
Total Budget				$236,601.83
Projected Budget/Expenditures for 2006				
		Projected 2007	2007 Anticipated Expenditures	
90600	Professional Salary - Jones	8,281.00	8,250.48	
90601	Professional Salary - Wang/Abdel	15,228.00	13,201.35	
90602	Professional Salary - Graham	26,368.00	26,073.98	
90702	Technician - Mechanical	3,037.00	2,968.53	
91000	Graduate Students - Monthly	26,600.00	27,300.00	
91800	Fringe Benefits (35%)	18,520.00	17,078.23	
95200	F&A (51%)	40,454.71	39,675.11	
Total Anticipated Expenditures as of 12/31/07		$138,488.71	$134,547.68	
Anticipated Fund Balance on 12/31/07				$ 102,054.15

Fluid Flow Projects

Advisory Board Meeting, November 6, 2007

2008 TUFFP Industrial Account Budget Summary

(Prepared October 25, 2007)

Anticipated Reserve Fund Balance on January 1, 2008		**$271,746.15**
Income for 2008		
	2008 Anticipated Membership Fees (17 @ $48,000 - excludes MMS)	**$816,000.00**
Total Income		**$1,087,746.15**
2008 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	28,474.96
90600-90609	Professional Salaries	96,359.54
90700-90703	Staff Salaries	24,228.72
91000	Graduate Students	65,000.00
91100	Undergraduate Students	15,000.00
91800	Fringe Benefits (33%)	49,190.86
93100	General Supplies	3,000.00
93101	Research Supplies	100,000.00
93102	Copier/Printer Supplies	500.00
93104	Computer Software	4,000.00
93106	Office Supplies	2,000.00
93200	Postage/Shipping	500.00
93300	Printing/Duplicating	2,000.00
93400	Telecommunications	3,000.00
93500	Memberships/Subscriptions	1,000.00
93601	Travel - Domestic	10,000.00
93602	Travel - Foreign	10,000.00
93700	Entertainment (Advisory Board Meetings)	10,000.00
81801	Tuition/Student Fees	53,219.70
94803	Consultants	16,000.00
94813	Outside Services	20,000.00
95200	Indirect Costs (55.6%)	127,359.15
98901	Employee Recruiting	3,000.00
99001	Equipment	200,000.00
99002	Computers	8,000.00
99300	Bank Charges	40.00
	Total Expenditures	**$851,872.94**
Anticipated Reserve Fund Balance on December 31, 2008		**$235,873.21**

2008 MMS Account Summary

(Prepared October 26, 2007)

Account Balance - January 1, 2008		**$5,321.94**
Income for 2008		
	2008 Membership Fee	**$40,000.00**
Remaining Balance		**$45,321.94**
2008 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	0.00
90600-90609	Professional Salaries	0.00
90700-90703	Staff Salaries	0.00
91000	Graduate Students	28,800.00
91800	Fringe Benefits (33%)	0.00
95200	Indirect Costs (55.6%)	16,012.80
	Total Expenditures	**$44,812.80**
Anticipated Reserve Fund Balance on December 31, 2008		**$509.14**

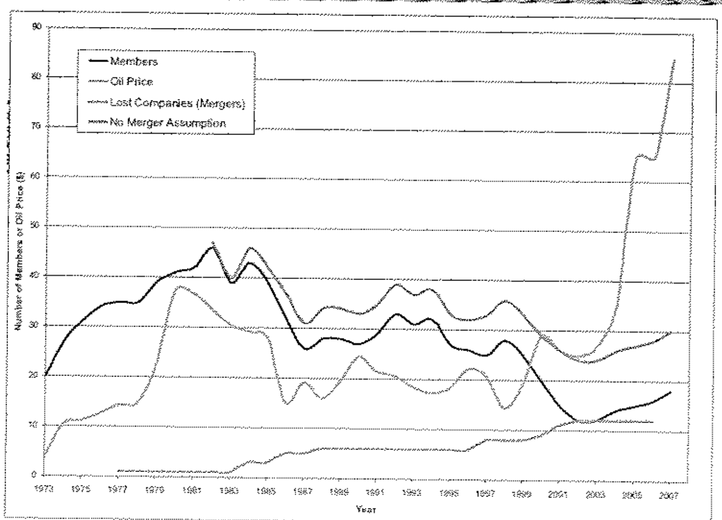
Fluid Flow Projects — Advisory Board Meeting, November 6, 2007

2008 DOE Account Summary

Award Amount	**$731,995.00**
Total Amount To Be Invoiced June 1, 2003 - December 31, 2007	**$629,940.85**
Remaining Balance	**$102,054.15**
2008 Anticipated Expenditures	**Projected Budget**
90101-90103 Faculty Salaries	0.00
90600-90609 Professional Salaries	39,168.27
90700-90703 Staff Salaries	10,469.41
91000 Graduate Students	7,000.00
91800 Fringe Benefits (33%)	16,380.43
95200 Indirect Costs (51%)	28,885.22
Total Expenditures	**$101,903.33**
Anticipated Reserve Fund Balance on December 31, 2008	**$150.82**

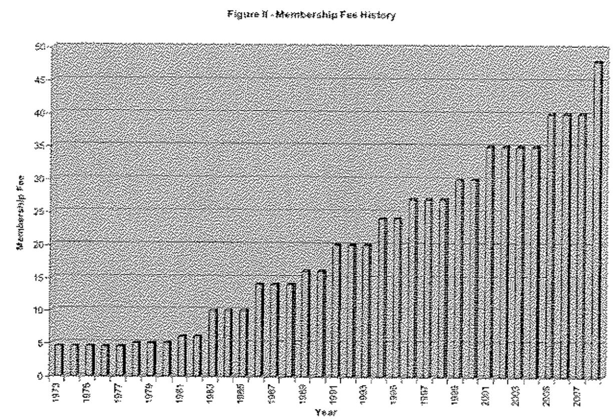
Fluid Flow Projects — Advisory Board Meeting, November 6, 2007

History – Membership



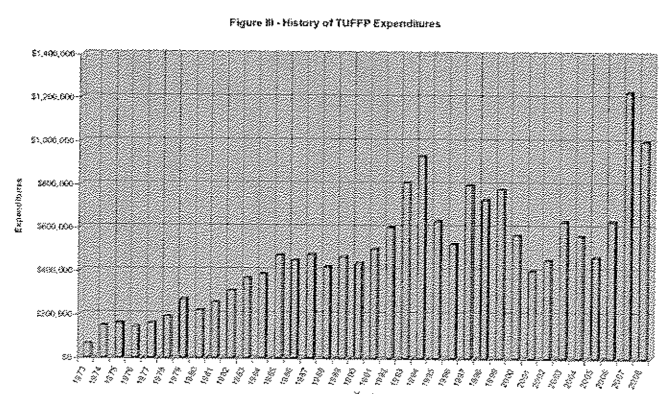
Fluid Flow Projects — Advisory Board Meeting, November 6, 2007

History – Membership Fees



Fluid Flow Projects Advisory Board Meeting, November 6, 2007

History - Expenditures



Fluid Flow Projects Advisory Board Meeting, November 6, 2007

Membership Fees

- 2007 Membership Dues
  - 15 of 18 Paid as of October 9^{th}

Introduction

This semi-annual report is submitted to Tulsa University Fluid Flow Projects (TUFFP) members to summarize activities since the April 24, 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 69th 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, November 6, 2007.

A facility tour will be held on November 5, 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. at ACAC. The Advisory Board meeting will convene at 8:00 a.m. on November 6th and will adjourn at approximately 5:30 p.m. Following the meeting, there will be a joint TUFFP and TUPDP reception between 6:00 and 9:00 p.m. at President's Lounge in ACAC.

The Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board meeting will be held on November 7th at ACAC between 8:00 a.m. and 1:00 p.m. Following the TUPDP meeting, the first Advisory Board meeting of Tulsa University High Viscosity Projects (TUHOP) will be held between 1:30 and 4:00 p.m. After the TUHOP meeting, there will be a joint TUPDP and Tulsa University Hydrate Flow Performance (TUHFP) Joint Industry Project (JIP) social function between 5:30-8:00 p.m. at President's Lounge in ACAC. The TUHFP Advisory Board meeting will be held on November 8th at ACAC between 8:00 a.m. and 2:00 p.m.

The reception and the social function will provide an opportunity for informal discussions among members, guests, and TUFFP, TUPDP, TUHFP 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 Spring 2008 Advisory Board meetings. The Spring 2008 Advisory Board meetings will be held at ACAC.

2008 Spring Meetings

March	Tulsa University Hydrate JIP (date to be determined – to follow DeepStar meeting)
April 22, 2008	Tulsa University High Viscosity Oil Projects (TUHOP) JIP Meeting Tulsa University Fluid Flow Projects (TUFFP) Workshop Facility Tour TUHOP – TUFFP Reception
April 23, 2008	Tulsa University Fluid Flow Projects (TUFFP) Advisory Board Meeting, TUFFP – TUPDP Reception
April 24, 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 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 is hired as the lead research associate for TUFFP after lengthy search process. 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. Abdel is currently responsible from TUFFP research projects.

Effective June 2007, Dr. Qian Wang resigned her position as Research Associate with TUFFP, TUPDP and TUCoRE High Viscosity Project to take a job with Scandpower USA. We wish her the best in her future endeavors.

Dr. Mingxiu (Michelle) Li has been hired as to the position vacated by Dr. Wang. 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. Michelle is currently assigned to a couple of short term TUCoRE projects and various TUFFP projects.

Dr. Shejiao Du continues as a research associate with TUCoRE Tulsa University High Viscosity Multiphase Project (TUHOP), TUPDP, and various contract projects.

Dr. Hong Chen's position with TUPDP has finally been filled. Dr. Wei Shang joined the team in September 2007. Dr. Wei has a Ph.D. from the University of Saskatchewan in Mechanical Engineering. After his graduation, he has conducted and supervised research projects in Thermodynamics-Fluids Lab as a research associate working under Professor Robert W. Besant at the same University. Currently, Wei serves as the lead Research Associate for TUPDP.

Ms. Anais Mathieu, a Scholar funded by Total, joined the TUPDP team this October. She is currently working on making TUWAX software CAPE-OPEN compliant and a research project in TUPDP.

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's position as part time technician was upgraded to full time. Brandon is a graduate of OSU Okmulgee with a BS degree in instrumentation and automation degree.

Mrs. Linda Jones continues as Project Coordinator of TUFFP, TUPDP and TUCoRE 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, continues as TUFFP/TUPDP Web Administrator. He is also serving as flow loop operator for TUPDP.

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. Serdar Atmaca, from Turkey, is recently completed his MS studies on oil-water flow in inclined pipes as continuation of Maria Vielma's study. Serdar will start working for Schlumberger Information Solutions immediately following the Advisory Board meeting.

Mr. Hongkun (Tom) Dong, from Peoples Republic of China, has also completed his MS studies on Three-phase Low Liquid Loading Flow in Horizontal Pipes. Tom will start working for ScandPower immediately following the Advisory Board meeting.

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 assigned to Three-phase Low Liquid Loading Flow Project to continue the project for inclined pipe configurations. He has helped Mr. Tom Dong during this Summer in experimental studies.

Mrs. Gizem Ersoy Gokcal, from Turkey, started her Ph.D. degree studies. She is working on the project titled "Multiphase 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.

Three new MS students joined TUFFP team in August. 2007. Mr. Kyle Magrini, a US National, received a BS degree in Electrical Engineering from The University of Tulsa. Kyle has already completed his deficiency course requirements in Petroleum Engineering and started to take graduate courses towards his MS degree requirements. He will be assigned a project after the Fall Advisory Board meeting. 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 will be conducting a research in three-phase multiphase flow area. 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 will be working on a project investigating multiphase flow in annulus and gas well unloading.

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

Table 1

2007 Fall Research Assistant Status

Name	*Origin*	*Stipend*	*Tuition*	*Degree Pursued*	*TUFFP Project*	*Completion Date*
Serdar Atmaca	Turkey	Yes – TUFFP	Yes – Waived	MS – PE	Two-Phase Oil-Water Flow in Inclined Pipes	August 2007
Kwon Il Choi	Brazil	No – Petrobras	No – Petrobras	Ph.D. – PE	Lagrangian-Eulerian Transient Two-Phase Flow Model	May 2008
Hongkun (Tom) Dong	PRC	Yes- TUFFP	Yes – TUFFP	MS – PE	Three-Phase Gas-Oil-Water Low Liquid Loading Flow	August 2007
Gizem Ersoy	Turkey	Yes – TUFFP	Yes – TUFFP	Ph.D. – PE	Multiphase Flow in Hilly Terrain Pipelines	May 2009
Xiao Feng	PRC	Yes – TUFFP	Yes – TUFFP	MS – PE	Three-Phase Gas-Oil-Water Low Liquid Loading Flow in Inclined Pipes	December 2008
Bahadir Gokcal	Turkey	Yes – TUFFP	Waived	Ph.D. – PE	High Viscosity Oil Multiphase Flow Behavior	May 2009
Kyle Magrini	USA	Yes – TUFFP	Yes – TUFFP	MS – PE	To be Assigned	Fall 2009
Anoop Sharma	India	Yes – TUFFP	Yes – TUFFP	MS – PE	Three-phase Flow	Fall 2009
Tingting Yu	PRC	Partial – TUFFP	No – PE Depart.	MS – PE	Multiphase Flow in an Annulus and Gas Well Unloading	Fall 2009

Membership

The current membership of TUFFP stands at 17 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.

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 2007 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

2007 Fluid Flow Projects Membership

Baker Atlas	Minerals Management Service
BP Exploration	PEMEX
Chevron	Petrobras
ConocoPhillips	Petronas
ExxonMobil	Rosneft
JOGMEG	Schlumberger
Kuwait Oil Company	Shell Global Solutions
Landmark Graphics	Tenaris
Marathon Oil Company	Total

Equipment and Facilities Status

Test Facilities

The high viscosity two-phase flow loop is modified to conduct Taylor Bubble velocity experiments. For future studies, the modifications are being designed to improve the phase separation.

Minor modifications are implemented to the three-phase facility to facilitate the inclined oil-water flow testing.

The low liquid loading facility modifications are completed and the first experimental study is completed.

Major modifications are planned for the 1,400 ft long hilly terrain flow facility. The facility will be converted to a three-phase facility by adding the water phase. Separation, liquid storage, pumping and meeting sections will be renewed. A new spill containment plans will also be implemented.

We are carefully designing a high pressure (500 psi operating pressures) and large diameter (6 in. ID) facility. Location of the facility is identified and site drawings are prepared. Most of the required equipment such as circulating gas compressor, cooler, liquid pumps, three-phase separator, and storage tanks have been identified.

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.

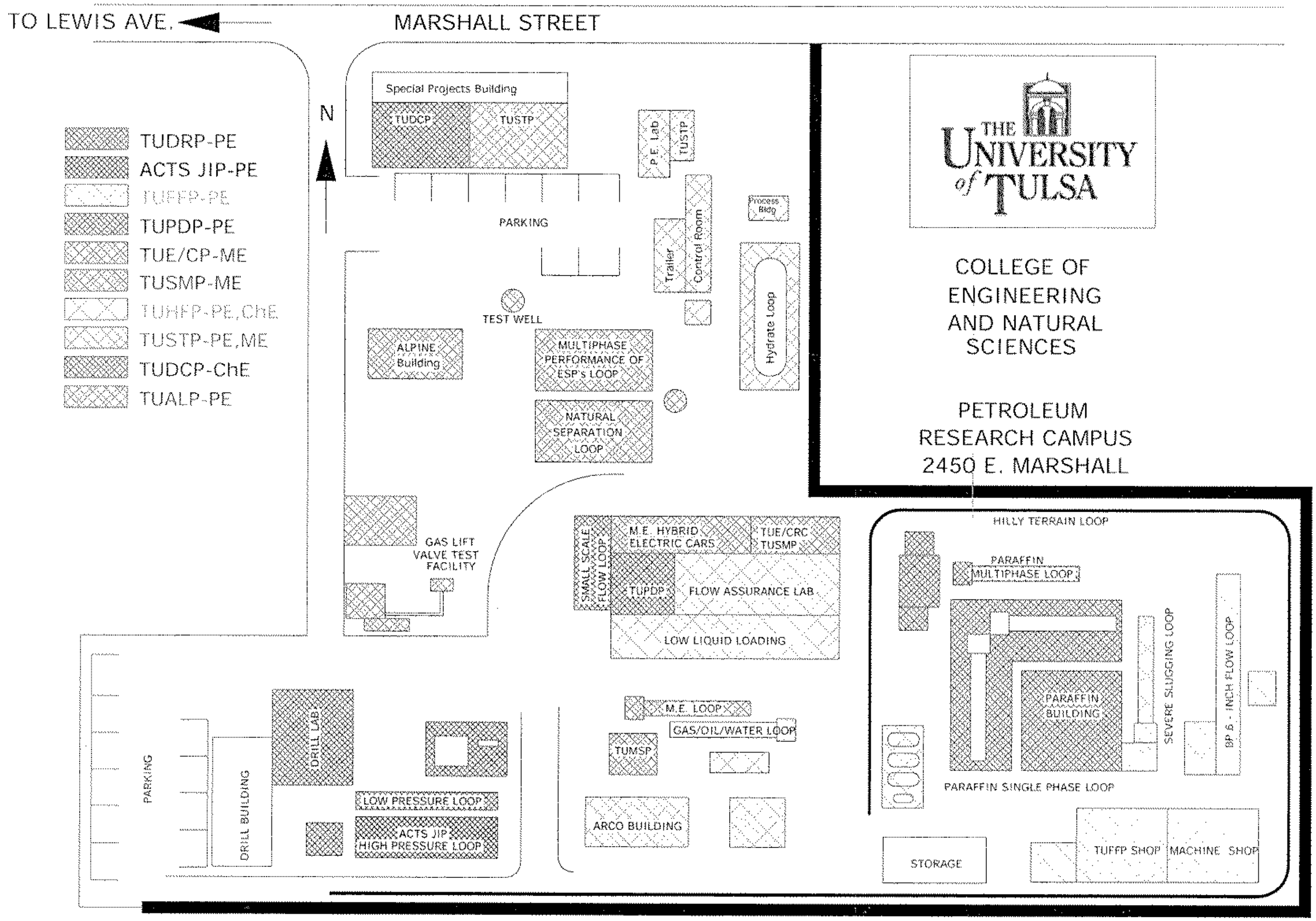


Figure 1 – Site Plan for the North Campus Research Facilities

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 October 9th, 2007, 15 of the 18 TUFFP members had paid their 2006 membership fees. The members who have not paid their membership fee were informed, and we expect to be paid soon.

Table 3 presents a financial analysis of income and expenditures for the 2007 Industrial member account as of October 22, 2007. Also shown are previous 2007 budgets that have been reported to the members. The project industry income for 2007 is $680,000 based on 17 industrial members. The industry account reserve fund balance on December 31, 2006 is $644,242. The total industry account expenditures for 2007 are projected to be $1,052,496. The industry reserve account is expected to be $271,746 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 $5,322 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 $134,548 will be spent in 2007, leaving an award balance of $102,054 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.

The DOE funding is ending by May 31, 2008. DOE support has been around $140,000 per year over the last five years. DOE funds allowed us to increase our activity by keeping the membership fee at the level of $40,000 over three years. With the ending of DOE support, the membership is increased to $48,000 for 2008. This is comparable to the other consortia membership fees at TU, e.g. TUALP - $44,000 TUPDP - $50,000, TUDRP - $52,500.

Tables 6-8 present the projected budgets and income for the Industrial, MMS, and DOE accounts for 2008. The 2008 TUFFP industrial membership is assumed to stay at 17 in this analysis. This will provide $816,000 of industrial membership income for 2008. The sum of the 2008 income and the reserve account is projected to be $1,087,746. The expenses for the industrial member account are estimated to be $851,873 leaving a balance of $235,873. The MMS account is expected to have a carryover of $509.

Table 3: TUFFP 2007 Industrial Budget

(Prepared October 22, 2007)

Reserve Fund Balance on January 1, 2007		**$644,242.26**
Income for 2007		
	2007 Membership Fees (15 @ $40,000 - excludes MMS)	**$600,000.00**
	2007 Membership Fees (1 @ 30,000)	**$30,000.00**
	2007 Membership Fees (1 @ 50,000)	**$50,000.00**
Total Budget		**$1,324,242.26**

Projected Budget/Expenditures for 2007

		Budget	Expenses 10/22/07	Anticipated 2007 Expenses
90101 - 90110	Faculty Salaries	52,698.00	41,164.59	43,726.37
90600 - 90609	Professional Salaries	61,372.00	51,323.00	58,873.70
90700 - 90800	Technician - Miller	35,680.00	30,403.56	36,752.74
91000	Graduate Students - Monthly	50,100.00	41,939.61	46,584.67
91100	Students - Hourly	15,000.00	18,768.68	22,000.00
91800	Fringe Benefits (35%)	50,910.83	39,063.68	46,584.67
93100	General Supplies	3,000.00	3,355.43	4,000.00
93101	Research Supplies	100,000.00	71,012.77	85,000.00
93102	Copier/Printer Supplies	500.00	162.84	250.00
93104	Computer Software	4,000.00	924.29	1,000.00
93106	Office Supplies	2,000.00	755.40	1,000.00
93200	Postage/Shipping	500.00	1,489.75	1,600.00
93300	Printing/Duplicating	2,000.00	1,624.69	2,200.00
93400	Telecommunications	3,000.00	1,653.59	2,000.00
93500	Membership/Subscriptions	1,000.00	384.00	500.00
93600	Travel		153.81	153.81
93601	Travel - Domestic	14,000.00	4,562.72	10,000.00
93602	Travel - Foreign	10,000.00	2,662.83	2,662.83
93606	Visa		-	
93700	Entertainment (Advisory Board Meetings)	10,000.00	4,961.06	10,000.00
94803	Consultants		7,708.35	10,791.69
94813	Outside Services	20,000.00	7,076.11	10,000.00
95200	F&A (55.6%)	119,456.33	102,081.29	115,613.24
98901	Employee Recruiting	3,000.00		4,000.00
99001	Equipment	600,000.00	2,904.41	482,000.00
99002	Computers	8,000.00	17,209.66	20,000.00
99300	Bank Charges	40.00	18.00	18.00
81801	Tuition/Fees	30,306.00	34,250.00	34,250.00
81806	Graduate Fellowship		519.71	934.39
	Total Expenditures	**$1,196,563.16**	**$488,133.83**	**$1,052,496.11**

Anticipated Reserve Fund Balance on December 31, 2007	**$ 271,746.15**

Table 4: TUFFP 2007 MMS Budget

(Prepared October 25, 2007)

Reserve Balance as of 12/31/06				**$6,109.94**
2007 Budget				**$40,000.00**
Total Budget				**$46,109.94**
Projected Budget/Expenditures for 2006				
		Budget	**2007 Anticipated 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 12/31/06		**$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

(Prepared October 24, 2007)

Award Amount		**$731,995.00**
Amount Invoiced (June 1, 2003 - December 31, 2006)		**$495,393.17**
Total Budget		**$236,601.83**

Projected Budget/Expenditures for 2006

		Projected 2007	**2007 Anticipated Expenditures**
90600	Professional Salary - Jones	8,281.00	8,250.48
90601	Professional Salary - Wang/Abdel	15,228.00	13,201.35
90602	Professional Salary - Graham	26,368.00	26,073.98
90702	Technician - Mechanical	3,037.00	2,968.53
91000	Graduate Students - Monthly	26,600.00	27,300.00
91800	Fringe Benefits (35%)	18,520.00	17,078.23
95200	F&A (51%)	40,454.71	39,675.11
Total Anticipated Expenditures as of 12/31/07		**$138,488.71**	**$134,547.68**

Anticipated Fund Balance on 12/31/07 **$ 102,054.15**

Table 6: 2008 Projected TUFFP Industrial Budget

(Prepared October 25, 2007)

Anticipated Reserve Fund Balance on January 1, 2008		**$271,746.15**
Income for 2008		
	2008 Anticipated Membership Fees (17 @ $48,000 - excludes MMS)	**$816,000.00**
Total Income		**$1,087,746.15**
2008 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	28,474.96
90600-90609	Professional Salaries	96,359.54
90700-90703	Staff Salaries	24,228.72
91000	Graduate Students	65,000.00
91100	Undergraduate Students	15,000.00
91800	Fringe Benefits (33%)	49,190.86
93100	General Supplies	3,000.00
93101	Research Supplies	100,000.00
93102	Copier/Printer Supplies	500.00
93104	Computer Software	4,000.00
93106	Office Supplies	2,000.00
93200	Postage/Shipping	500.00
93300	Printing/Duplicating	2,000.00
93400	Telecommunications	3,000.00
93500	Memberships/Subscriptions	1,000.00
93601	Travel - Domestic	10,000.00
93602	Travel - Foreign	10,000.00
93700	Entertainment (Advisory Board Meetings)	10,000.00
81801	Tuition/Student Fees	53,219.70
94803	Consultants	16,000.00
94813	Outside Services	20,000.00
95200	Indirect Costs (55.6%)	127,359.15
98901	Employee Recruiting	3,000.00
99001	Equipment	200,000.00
99002	Computers	8,000.00
99300	Bank Charges	40.00
	Total Expenditures	**$851,872.94**
Anticipated Reserve Fund Balance on December 31, 2008		**$235,873.21**

Table 7: TUFFP Projected 2008 MMS Budget

(Prepared October 26, 2007)

Account Balance - January 1, 2008		**$5,321.94**
Income for 2008		
	2008 Membership Fee	**$40,000.00**
Remaining Balance		**$45,321.94**
2008 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	0.00
90600-90609	Professional Salaries	0.00
90700-90703	Staff Salaries	0.00
91000	Graduate Students	28,800.00
91800	Fringe Benefits (33%)	0.00
95200	Indirect Costs (55.6%)	16,012.80
	Total Expenditures	**$44,812.80**
Anticipated Reserve Fund Balance on December 31, 2008		**$509.14**

Table 8: TUFFP Projected 2008 DOE Budget

Award Amount		**$731,995.00**
Total Amount To Be Invoiced		
	June 1, 2003 - December 31, 2007	**$629,940.85**
Remaining Balance		**$102,054.15**
2008 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	0.00
90600-90609	Professional Salaries	39,168.27
90700-90703	Staff Salaries	10,469.41
91000	Graduate Students	7,000.00
91800	Fringe Benefits (33%)	16,380.43
95200	Indirect Costs (51%)	28,885.22
	Total Expenditures	**$101,903.33**
Anticipated Reserve Fund Balance on December 31, 2008		**$150.82**

Miscellaneous Information

Fluid Flow Projects Short Course

The 33[nd] 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.

6[th] 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. Although the abstract deadline passed, it is encouraged to submit late abstracts. 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. Fan Y., Wang, Q., Zhang, H. Q., **Sarica, C.,** and Danielson, T.: "A Model To Predict Liquid Holdup and Pressure Gradient of Near-Horizontal Wet-Gas Pipelines," SPE 95674, *SPE Projects, Facilities & Construction Journal,* June 2007.
2. 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, Accepted for Publication in *SPE Production & Operations Journal,* 2007.
3. Al-Safran, E. and **Sarica, C.** "Experimental Investigation of Two-phase Flow Behavior at the Top Elbow of a Hilly-Terrain Pipeline," Proceedings of 13[th] International Conference Multiphase Production 07, Edinburgh, UK, June 13-15, 2007.

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, Chevron and Petrobras.

Two-Phase Flow Calendar

Several technical meetings, seminars, and short courses involving two-phase flow in pipes are scheduled for 2007 and 2008. Table 9 lists meetings that would be of interest to TUFFP members.

Table 9

Meeting and Conference Calendar

2008

March	TUHOP Spring Advisory Board meeting, Tulsa, OK Date to be determined – to follow DeepStar meeting.
April 22	TUFFP Spring Workshop, Tulsa, OK
April 23	TUFFP Spring Advisory Board meeting, Tulsa, OK
April 24	TUPDP Spring Advisory Board meeting, Tulsa, OK
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 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).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

63. "Prudhoe Bay Large Diameter Slug Flow Experiments and Data Base System" Users Manual, by S. L. Scott (July 1989).

64. "Two-Phase Slug Flow in Upward Inclined Pipes", by G. Zheng (Dec. 1989).

65. "Elimination of Severe Slugging in a Pipeline-Riser System," by F. E. Jansen (May 1990).

66. "A Mechanistic Model for Predicting Annulus Bottomhole Pressures for Zero Net Liquid Flow in Pumping Wells," by D. Papadimitriou (May 1990).

67. "Evaluation of Slug Flow Models in Horizontal Pipes," by C. A. Daza (May 1990).

68. "A Comprehensive Mechanistic Model for Two-Phase Flow in Pipelines," by J. J. Xiao (Aug. 1990).

69. "Two-Phase Flow in Low Velocity Hilly Terrain Pipelines," by C. Sarica (Aug. 1990).

70. "Two-Phase Slug Flow Splitting Phenomenon at a Regular Horizontal Side-Arm Tee," by S. Arirachakaran (Dec. 1990)

71. "RECENT PUBLICATIONS" - A collection of articles based on previous TUFFP research reports that have been published or are under review for various technical journals (May 1991).

72. "Two-Phase Flow in Horizontal Wells," by M. Ihara (October 1991).

73. "Two-Phase Slug Flow in Hilly Terrain Pipelines," by G. Zheng (October 1991).

74. "Slug Flow Phenomena in Inclined Pipes," by I. Alves (October 1991).

75. "Transient Flow and Pigging Dynamics in Two-Phase Pipelines," by K. Minami (October 1991).

76. "Transient Drift Flux Model for Wellbores," by O. Metin Gokdemir (November 1992).

77. "Slug Flow in Extended Reach Directional Wells," by Héctor Felizola (November 1992).

78. "Two-Phase Flow Splitting at a Tee Junction with an Upward Inclined Side Arm," by Peter Ashton (November 1992).

79. "Two-Phase Flow Splitting at a Tee Junction with a Downward Inclined Branch Arm," by Viswanatha Raju Penmatcha (November 1992).

80. "Annular Flow in Extended Reach Directional Wells," by Rafael Jose Paz Gonzalez (May 1994).

81. "An Experimental Study of Downward Slug Flow in Inclined Pipes," by Philippe Roumazeilles (November 1994).

82. "An Analysis of Imposed Two-Phase Flow Transients in Horizontal Pipelines Part-1 Experimental Results," by Fabrice Vigneron (March 1995).

83. "Investigation of Single Phase Liquid Flow Behavior in a Single Perforation Horizontal Well," by Hong Yuan (March 1995).

84. "1995 Data Documentation User's Manual", (October 1995).

85. "Recent Publications" A collection of articles based on previous TUFFP research reports that have been published or are under review for various technical journals (February 1996).

86. "1995 Final Report - Transportation of Liquids in Multiphase Pipelines Under Low Liquid Loading Conditions", Final report submitted to Penn State University for subcontract on GRI Project.

87. "A Unified Model for Stratified-Wavy Two-Phase Flow Splitting at a Reduced Tee Junction with an Inclined Branch Arm", by Srinagesh K. Marti (February 1996).

88. "Oil-Water Flow Patterns in Horizontal Pipes", by José Luis Trallero (February 1996).

89. "A Study of Intermittent Flow in Downward Inclined Pipes" by Jiede Yang (June 1996).

90. "Slug Characteristics for Two-Phase Horizontal Flow", by Robert Marcano (November 1996).

91. "Oil-Water Flow in Vertical and Deviated Wells", by José Gonzalo Flores (October 1997).

92. "1997 Data Documentation and Software User's Manual", by Avni S. Kaya, Gerad Gibson and Cem Sarica (November 1997).

93. "Investigation of Single Phase Liquid Flow Behavior in Horizontal Wells", by Hong Yuan (March 1998).

94. "Comprehensive Mechanistic Modeling of Two-Phase Flow in Deviated Wells" by Avni Serdar Kaya (December 1998).

95. "Low Liquid Loading Gas-Liquid Two-Phase Flow in Near-Horizontal Pipes" by Weihong Meng (August 1999).

96. "An Experimental Study of Two-Phase Flow in a Hilly-Terrain Pipeline" by Eissa Mohammed Al-Safran (August 1999).

97. "Oil-Water Flow Patterns and Pressure Gradients in Slightly Inclined Pipes" by Banu Alkaya (May 2000).

98. "Slug Dissipation in Downward Flow – Final Report" by Hong-Quan Zhang, Jasmine Yuan and James P. Brill (October 2000).

99. "Unified Model for Gas-Liquid Pipe Flow – Model Development and Validation" by Hong-Quan Zhang (January 2002).

100. "A Comprehensive Mechanistic Heat Transfer Model for Two-Phase Flow with High-Pressure Flow Pattern Validation" Ph.D. Dissertation by Ryo Manabe (December 2001).

101. "Revised Heat Transfer Model for Two-Phase Flow" Final Report by Qian Wang (March 2003).

102. "An Experimental and Theoretical Investigation of Slug Flow Characteristics in the Valley of a Hilly-Terrain Pipeline" Ph.D. Dissertation by Eissa Mohammed Al-safran (May 2003).

103. "An Investigation of Low Liquid Loading Gas-Liquid Stratified Flow in Near-Horizontal Pipes" Ph.D. Dissertation by Yongqian Fan.

104. "Severe Slugging Prediction for Gas-Oil-Water Flow in Pipeline-Riser Systems," M.S. Thesis by Carlos Andrés Beltrán Romero (2005)

105. "Droplet-Homophase Interaction Study (Development of an Entrainment Fraction Model) – Final Report," Xianghui Chen (2005)

106. "Effects of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes" M.S. Thesis by Bahadir Gokcal (2005)

107. "Characterization of Oil-Water Flows in Horizontal Pipes" M.S. Thesis by Maria Andreina Vielma Paredes (2006)

Appendix B

2007 Fluid Flow Projects Advisory Board Representatives

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Appendix C

History of Fluid Flow Projects Membership

	1973		
1.	TRW Reda Pump	12 Jun. '72	T: 21 Oct. '77
2.	Pemex	15 Jun. '72	T: 30 Sept. '96 R: Dec '97 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	**Current**
	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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