Title: Advanced Cuttings Transport Study

Type of Report: Quarterly Technical

Reporting Period Start Date: April 1, 2002

Reporting Period End Date: June 30, 2002

Principal Authors:

Troy Reed, Principal Investigator

Stefan Miska, Co-Principal Investigator

Nicholas Takach, Co-Principal Investigator

Kaveh Ashenayi, Co-Principal Investigator

Mark Pickell, Project Engineer

Len Volk

Mike Volk

Evren Ozbayoglu

Lei Zhou

Date of Issue: July 30, 2002

DOE Award Number: DE-FG26-99BC15178

The University of Tulsa
600 South College Avenue
Tulsa, Oklahoma 74104

Title: Advanced Cuttings Transport Study

Type of Report: Quarterly

Reporting Period Start Date: April 1, 2002

Reporting Period End Date: June 30, 2002

Principal Authors:

Troy Reed, Principal Investigator

Stefan Miska, Co-Principal Investigator

Nicholas Takach, Co-Principal Investigator

Kaveh Ashenayi, Co-Principal Investigator

Mark Pickell, Project Engineer

Len Volk

Mike Volk

Evren Ozbayoglu

Lei Zhou

Date of Issue: July 30, 2002

DOE Award Number: DE-FG26-99BC15178

The University of Tulsa
600 South College Avenue
Tulsa, Oklahoma 74104

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government, Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply, its endorsement, recommendation, or favoring, by the United States Government or agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

1. SUMMARY OF CURRENT TASKS FOR ACTS PROJECT

This is the fourth quarterly progress report for Year-3 of the ACTS Project. It includes a review of progress made in: 1) Flow Loop construction and development and 2) research tasks during the period of time between April 1, 2002 and June 30, 2002.

This report presents a review of progress on the following specific tasks:

- a) Design and development of an Advanced Cuttings Transport Facility
(**Task 3**: Addition of a Cuttings Injection/Separation System),
- b) Research project (**Task 6**): “ Study of Cuttings Transport with Foam Under LPAT Conditions (Joint Project with TUDRP)”,
- c) Research project (**Task 9b**): “ Study of Foam Flow Behavior Under EPET Conditions”,
- d) Research project (**Task 10**): “Study of Cuttings Transport with Aerated Mud Under Elevated Pressure and Temperature Conditions”,
- e) Research on three instrumentation tasks to measure:
 - Cuttings concentration and distribution in a flowing slurry (**Task 11**), and
 - Foam texture while transporting cuttings. (**Task 12**),
 - Viscosity of Foam under EPET (**Task 9b**)
- f) Development of a Safety program for the ACTS Flow Loop.
Progress on a comprehensive safety review of all flow-loop components and operational procedures. (**Task 1S**).
- g) Activities towards technology transfer and developing contacts with Petroleum and service company members, and increasing the number of JIP members.

2. EXECUTIVE SUMMARY OF PROGRESS

Flow Loop Construction (Task 3)

During the third quarter, Year-3 of the ACTS Project, a new Cuttings Injection/Separation system was installed. During the fourth quarter, the task of commissioning this system was initiated. In addition, work continued on completing the new “Field Point” data acquisition system. The major construction milestones for Year-3 of the ACTS Project have been achieved.

The planned piping modifications, instrumentation additions, and new Field Point wiring additions are nearing completion. Startup, check-out, and basic computer controls (software) are completed. Two nuclear densitometers have been calibrated for 3-phase (gas/liquid/solids) slurry flows. A new simulated drill string has been constructed which includes two short sections of nylon pipe located at the same axial stations as the nuclear densitometers. Delivery of the view ports has been extended until problems are resolved concerning failures of the 2” and 3” during pressure tests by the manufacturer. Two other new additions include:

1) a larger capacity centrifugal pump to feed the Halliburton Frac Pump and the Moyno Triphase Pump, and 2) new piping which will enable the flushing of cuttings from the Drilling Section as part of a “hold-up” measurement to quantify the three volume fractions of each constituent in a cuttings-transport slurry. Finally, arrangements are being made for the installation of a new “Super-Auto Drilling Choke” that will be donated by SWACO.

Additional discussion of the Flow Loop is given in Section 3 of this report.

Study of Cuttings Transport with Foam Under LPAT Conditions, (Task 6).

All cuttings-transport tests with foam in the Low Pressure/Ambient Temperature Flow Loop have been completed. A computer simulator has been developed based on a 3-layer cuttings-transport model. Additional modeling efforts include a conventional engineering correlation and an Artificial Neural Network (ANN) Model for estimating bed heights. The ANN Model provides the most accurate correlation of the experimental data. A Ph.D. dissertation has been completed, and copies have been provided to the DOE and all JIP members. A summary of this work is provided in Section 4.

Study of Foam Flow Behavior Under EPET Conditions, (Task 9).

This project was completed during the second quarter of Year-3. A summary of the results and conclusions were presented in the DOE Quarterly Report for that period. Copies of the MS thesis report have been provided to the DOE and all JIP members.

One of the important findings from this research task is that foam texture (i.e., bubble size, shape & size distribution) has a primary effect on the apparent viscosity of a foam. This identified the need to have an instrument that can generate a foam with a controlled bubble size and then measure its rheological properties. This has led to the development of a new concept for achieving these objectives. This will become a new instrumentation task, and it will be designated **Task 9b**. Measurements of foam

viscosity will supplement the optical measurements of foam texture that is part of Task 12. TU is currently considering filing an application for a US Patent. If a decision is made to file a patent, the appropriate forms will be submitted to the DOE. Additional discussion of the Foam Generator/Viscometer is given in Section 5 of this report.

Study of Cuttings Transport with Aerated Mud Under Elevated Pressure and Temperature Conditions, (Task 10).

Detailed studies of previous TUDRP/ACTS projects and a literature review of related subjects are continuing. Theoretical analyses of cuttings-transport phenomena, based on layered models, are under development. One approach is to extend R.D. Kaminsky's¹ Non-Newtonian fluid flow model to annular geometries. In addition, studies of the instability of cuttings beds, when sheared by viscous flows, are in progress. A new capability to flush the Drilling Section and measure the cuttings trapped in this annular test section is being constructed and is expected to be operational during the first quarter of Year-4. This will provide essential data for development of a cuttings-transport model. Additional discussion of this task is provided in Section 6.

Research on Instrumentation to Measure Cuttings Concentration and Distribution in a Flowing Slurry, (Task 11).

The modifications and testing of the printed circuit boards and firmware (previously developed and reported) have been completed. The final version of the board is being produced. The data acquisition software has also been modified. The results from this modified system indicate that we are able to distinguish between different sand concentrations. Tests have also determined that the ultra-sonic sensors can be used to detect cuttings even when a solid plastic cap is to hold and separate them from a slurry. In order to account for the nonlinear nature of a slurry flow, an artificial neural network model will be used to analyze and process the signals and produce the desired data on cuttings concentration. A review of progress on this task is given in Section 7.

Research on Instrumentation to Measure Foam Properties while Transporting Cuttings, (Task 12).

Microphotographs were taken of foam generated by various means. Several minor modifications/improvements to the Dynamic Testing Facility (DTF) have been completed. Both the average bubble size and foam quality techniques were applied to blender-generated foam. Foam stability was found to be less than anticipated which is shifting bubble characterization efforts to the DTF and dynamic foam. The status of this work is reviewed in Section 8.

Safety Program for the ACTS Flow Loop, (Task 1S)

The Action Plan continues to be the primary focus of Task 1S. Additional discussion of this task appears in Section 9.

Activities towards Technology Transfer, Developing Contacts with Petroleum &

Service Company Members, and Addition of JIP Members.

The May 2002 Advisory Board Meeting was well attended. In addition to existing JIP members (see Section 10), a number of companies attended as guests. In particular, ExxonMobil had three representatives, Anadarko Petroleum had one person, and Grant Prideco had two people attend this meeting. After attending this meeting, ExxonMobil indicated an interest in joining the project.

In early June, a presentation was made to MI Drilling personnel at their headquarters in Houston. They have also indicated a definite interest in joining the ACTS Project. Contacts with other petroleum and service companies will be pursued. Further discussion of these activities is given in Section 10.

TABLE OF CONTENTS

DISCLAIMER	2
1. SUMMARY OF CURRENT TASKS FOR ACTS PROJECT	3
2. EXECUTIVE SUMMARY OF PROGRESS	4
LIST OF FIGURES	8
3. ACTF DESIGN AND CONSTRUCTION ACCOMPLISHMENTS	9
4. STUDY OF CUTTINGS TRANSPORT WITH FOAM UNDER LPAT CONDITION	11
5. STUDY OF FOAM FLOW BEHAVIOR UNDER EPET CONDITIONS	13
6. STUDY OF CUTTINGS TRANSPORT WITH AERATED MUDS UNDER EPAT CONDITIONS	14
7. DEVELOPMENT OF CUTTINGS MONITORING METHODOLOGY	23
8. DEVELOPMENT OF METHODS FOR CHARACTERIZING BUBBLES IN IN ENERGIZED FLUIDS	26
9. SAFETY PROGRAM	29
10. TECHNOLOGY TRANSFER	31

LIST OF FIGURES

ACTF DESIGN AND CONSTRUCTION (Task 3)

Figure 3.1 – ACTS Flow Loop with Separation Tower and Cuttings Injection Hopper with Loading Auger	9
---	---

STUDY OF CUTTINGS TRANSPORT WITH AERATED MUD UNDER EPET (Task 10, Sec. 6)

Figure 6.1 – Cuttings Bed in the Calibration Gig	16
Figure 6.2 – Calibration of a Nuclear Densitometer	18
Figure 6.3 – Couette Flow over a Wavy Bed	20
Figure 6.4 – Schematic of a Couette Resuspension Flow	20

3. ACTF DESIGN AND CONSTRUCTION ACCOMPLISHMENTS

All planned piping modifications, instrumentation additions, and new Field Point wiring additions are nearing completion.

Figure 3.1 – ACTS Flow Loop with Separation Tower and Cuttings Injection Hopper with Loading Auger

Startup and check-out of the computer controls (software) has been completed for the basic functions. In addition, two nuclear densitometers have been calibrated for 3-phase (gas/liquid/solids) slurry flows. According to the manufacturer of these nuclear densitometers (Ronan Engineering), we are the first to apply this type of instrument to a 3-phase slurry. Furthermore, a new drillpipe has been constructed that includes two short sections of nylon pipe located at the same axial stations as the nuclear densitometers. Preliminary test runs have been very encouraging in that everything is working as designed. More complex computer control functions will be added on an as-needed basis as tests are conducted over the entire range of Flow-Loop variables.

We have been advised that all view ports have been completed by the manufacture. However, the two and three-inch view ports failed during pressure tests at about 500 psi. The vendor is working closely with the glass supplier (Corning) to determine why the failures occurred and find a solution. Delivery has been extended until the problem is resolved. In addition to the planned work, a larger capacity jockey (centrifugal) pump has been installed to feed the Halliburton Frac Pump and the Moyno Triphase Pump. This will allow us to take full advantage of the piping installed last spring which enables operation of the Halliburton and the Moyno pumps simultaneously, in parallel. In addition, new piping is being added which will enable the flushing of cuttings from the

Drilling Section. This will allow the cuttings to be flushed to the Separation Tower and weighed. Then their volume fraction can be determined as part of a “hold-up” measurement. (The objective of a “hold-up” measurement is to determine the volume fraction of the three components: gas, liquid and solids.)

An additional choke is needed between the slurry exiting the flow loop and the Separation Tower. This is necessary because the Separation Tower is designed for a maximum working pressure of 1500 psi versus the test sections of the Flow Loop which can operate at pressures up to 2,000 psi. Hence, this choke will be used to reduce pressures when tests are conducted at pressures above 1500 psi. This will only occur when tests are conducted with conventional (incompressible) drilling fluids. However, this choke can also be used to allow additional expansion of a compressible flow to assist the pumping of a slurry up to the entrance into the Separation Tower. In addition, this new choke must also be able to endure the erosion created by a fast-moving slurry. A choke manufactured by SWACO has been proven in field drilling operations to meet this requirement. Hence, we are happy to report that SWACO has reconfirmed their donation of a Super-Auto Drilling Choke. Arrangements are now being made for installation of this new choke.

4. STUDY OF CUTTINGS TRANSPORT WITH FOAM UNDER LPAT CONDITIONS (Task 6)

Investigator: Evren Ozbayoglu (Ph.D. Candidate)

OBJECTIVES

- To investigate foam rheology and flow behavior in pipe and annulus.
- To determine (experimentally) and to predict (analytically) frictional pressure losses (with and without cuttings) and volumetric requirements (injection rate, injection pressure and backpressure) for effective cuttings transport with foam flow in inclined and horizontal wellbores.

PROJECT STATUS

- Development of a 3-Layer Cuttings Transport Model has been completed. The Model can determine pressure losses, layer velocities, in-situ cuttings concentration, cuttings bed thickness and slip velocity between the cuttings and the fluid.
- Development of a computer simulator, based on the proposed model, is completed.
- Empirical equations and an Artificial Neural Network Model were developed for estimating cuttings bed thickness in a wellbore for a given set of drilling conditions.
- Simulator results are compared with experimental data. Also, experimental bed-thickness measurements are compared with simulator results, empirical correlations and the ANN results.
- A Ph.D. dissertation has been completed and distributed to the DOE and all JIP members.

SUMMARY OF RESULTS

Foams are of considerable interest for annular pressure management in many drilling applications. While foam rheology and hydraulics have been studied in the past, knowledge of cuttings transport with foam is very limited for vertical wells, and even less well understood for horizontal and inclined-well configurations. This work analyzes cuttings transport with foam in horizontal and highly-inclined wells.

Using the principles of mass and linear momentum conservation, a model consisting of three-layers (motionless bed – observed in most experiments, moving foam-cuttings mixture and foam free-of-cuttings) is presented. The model includes seven independent equations and seven unknowns. A computer simulator was developed to solve simultaneously the system of equations for flow velocities, cuttings bed height, slip velocity, the in-situ concentration of flowing cuttings and pressure drop.

An extensive experimental program on cuttings transport was conducted using The University of Tulsa Drilling Research Projects' full-scale (8" by 4 ½") flow loop at 70° to 90° inclinations (from vertical). A broad range of annular velocities and cuttings injection rates was investigated using foam qualities of 70% to 90%. Results from the

experiments are presented in the form of graphs showing the cuttings bed cross-sectional area and pressure losses vs foam flow rate. In all experiments, the foam behaved as a pseudo-plastic fluid; foam qualities of 80% and 90% exhibited noticeable wall slip. At a given flow rate and rate of cuttings injection, bed thickness increases with an increase in foam quality. There is little effect of inclination angles in the range of 70°-90°.

The experimental data were used to verify results from the simulator. The simulator is capable of estimating bed thickness and pressure drop with an error of less than 20% in most cases. In addition to the simulator, two other models were developed to predict bed heights, viz., a conventional engineering correlation and an Artificial Neural Networks Model. The ANN Model provides the best over-all predictions of bed heights.

CONCLUSIONS

The major conclusions from this study are as follows:

- The foam, used in this study, behaves like a pseudo-plastic fluid with a negligible yield stress.
- Pressure losses can be determined using the proposed generalized model in pipes and annular geometries mostly with an error of less than 20%.
-
- Turbulent flow is the key for effective cuttings transport in horizontal and inclined wellbores. When compared with water, the tendency to build a cuttings bed with foam is higher at the same flow rates for horizontal and highly-inclined wellbores. Very high velocities are required to prevent the development of a thick cuttings bed, when foam is used as the circulating fluid.
-
- Thickness of the bed increases as foam quality increases for a constant in-situ flow rate.
- Inclination angle has a negligible effect on bed thickness for angles between 70°-90°.
- For horizontal and highly-inclined wellbores, a 3-layer model is used to determine bed thickness and pressure loss. A simulator is developed based on this model. The program can be used to assist designing wells and determining the volumetric flow rates of liquid and gas phase for a particular drilling condition.
- For practical purposes, a conventional empirical correlation, as well as an Artificial Neural Networks (ANN) Model, can be used to estimate bed thickness.

5. STUDY OF FOAM FLOW BEHAVIOR UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS (Task 9)

Investigator: Affonso Marcelo Fernandes Lourenço (MS Graduate)

OBJECTIVES

- Perform experimental study of foam flow behavior inside pipes and annuli in a large-scale loop (ACTS) under elevated pressure and temperature.
- Develop empirical correlations to estimate pressure losses during foam flow for a given set of gas-liquid ratio, temperature and pressure conditions.

SUMMARY OF ACTIVITIES

- Work on this research (Task 9) has now been completed. Copies of the thesis report have been provided to the DOE and all JIP sponsors.

One of the important findings from this hydraulic study of foam is that bubble size has a primary effect on the apparent viscosity of a foam. This identified the need to have an instrument that can generate foam with a controlled bubble size and then measure its rheological properties. This has led to the development of a new concept for achieving these objectives. In particular, there is currently a need for an instrument that can generate a foam and measure its viscous properties. The instrument should be capable of controlling the following six variables independently. 1) foam quality (ratio of gas to liquid), 2) pressure, 3) temperature, 4) surfactants and other additives, 5) bubble size, and 6) surface roughness inside a viscometer. A survey of different manufacturers of viscometers and rheometers found that there is currently no commercially available instruments designed to accomplish the above list of measurements for foams

TU is presently evaluating the filing of a US patent application for this new instrument. If the decision is made to file for a patent, then the appropriate forms will be submitted to the DOE. In addition, the details will be shared with the ACTS JIP members.

6. STUDY OF CUTTINGS TRANSPORT WITH AREATED MUD UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS (TASK 10)

Investigator: Lei Zhou (Ph.D. Candidate)

6.1 Objectives

1. Develop two-phase flow model for aerated fluids under elevated pressure and temperature conditions inside annuli in a horizontal position without pipe rotation.
2. Determine experimentally the cuttings transport ability of aerated fluids under elevated pressure and temperature conditions.
3. Determine the optimum gas/liquid flow rates for cuttings transport.
4. Develop a computational tool to calculate pressure loss in aerated fluids flowing under elevated pressure and high temperature conditions.

6.2 Past Work

1. Literature review on cuttings transport and hole cleaning.
2. Literature review on cuttings bed stability analysis.
3. Loaded cuttings into injection tower.
4. Finalized calibration of nuclear densitometers. (calibration curve developed)
5. Pressure drop and holdup calculation for Non-Newtonian fluid flow with air (two-phase) using R.D. Kaminsky's method.
6. Modified R.D. Kaminsky's method to larger pipe diameter and inclined angles, using Taitel&Dukler's² method to calculate the "holdup".

6.3 Present Work

1. Modify R.D. Kaminsky's method so it applies equally well to annular geometries.
2. Develop a numerical simulator to solve the layered model equations for cuttings transport in annuli.
3. Analyze the role that cuttings-bed instability has in cuttings transport for drilling operations.

Calibration of Nuclear Densitometers

Calibration work for the nuclear density monitors has been finalized. Some new methods have been used to simulate the desired test situation. In the last DOE report, the need for a multi-Point calibration procedure was discussed versus a simple Dual-Point calibration that is considered to be standard procedure. The results of our tests show that the radiation field is not uniform across the annular space (there are ten seeds of Cesium 137 distributed along the length of two separate holder cells that are mounted parallel to each other but transverse to the axis of the annulus). This causes different locations to receive different amounts of radiation.

We also assumed that there could be differences between the two nuclear densitometers. So the two densitometers were calibrated separately instead of inputting the counts we got from the first one to the second one. The manufacturer stated that the difference between the two densitometers is very small, and we did try to input the acquired counts from the first calibrated densitometer to the second one. The result showed the statement is fairly true for water test. But when a cuttings bed is added to the space, a deviation between the two is observed.

A carefully measured amount of cuttings was added by using a small tool consisting of a pipe cut in-half along its axis. It has the same length as the Calibration Gig. Cuttings were placed in the tool along its length and then inserted into the Calibration Gig and turned upside down to load the annular space. This produced a nearly uniform bed in the annulus. (see Figure 6.1)

The volume of the annular space within the Calibration Gig was carefully measured in order to achieve an accurate calculation of mixture densities. There exists a difference of volume between the lower part of the test section and upper part. So when the mixture density was calculated, this difference in geometry was properly accounted for.

Figure 6.1 - Cuttings Bed in the Calibration Gig

Two sets of reference ranges are planned for the densitometers. One set is for two-phase flow experiments. The low reference value of density is set when the annulus is full filled with air; a high reference value of density is set when the annulus is fully filled with water. The second density range is for cuttings transport with aerated fluids. The low reference value is set when one half of the annulus is filled with water and packed cuttings and the top half is simply air. The high reference value for the second density range is set when the annulus is 75% filled with cuttings and the remaining space is filled with water.

The following page shows the calculations of mixture density for different ratios of cuttings and water.

$$V_{\text{tray}} := 3210$$

$$V_{\text{upper}} := 3175$$

$$\rho_s := 2.613$$

$$\rho_w := 0.998$$

$$P := 0.385$$

25 % cuttings and 75% of water

$$\rho_{\text{mix}} := \frac{\rho_s \cdot \left(\frac{V_{\text{tray}}}{2} \right) \cdot (1 - P) + \rho_w \cdot \left[V_{\text{tray}} + V_{\text{upper}} - \left(\frac{V_{\text{tray}}}{2} \right) \cdot (1 - P) \right]}{V_{\text{tray}} + V_{\text{upper}}}$$

$$\rho_{\text{mix}} = 1.248$$

50 % cuttings and 50% of water

$$\rho_{\text{mix}} := \frac{\rho_s \cdot (V_{\text{tray}}) \cdot (1 - P) + \rho_w \cdot [V_{\text{tray}} + V_{\text{upper}} - (V_{\text{tray}}) \cdot (1 - P)]}{V_{\text{tray}} + V_{\text{upper}}}$$

$$\rho_{\text{mix}} = 1.497$$

75 % cuttings and 25% of water

$$\rho_{\text{mix}} := \frac{\rho_s \cdot \left(V_{\text{tray}} + \frac{V_{\text{upper}}}{2} \right) \cdot (1 - P) + \rho_w \cdot \left[V_{\text{tray}} + V_{\text{upper}} - \left[\left(\frac{V_{\text{upper}}}{2} \right) + V_{\text{tray}} \right] \cdot (1 - P) \right]}{V_{\text{tray}} + V_{\text{upper}}}$$

$$\rho_{\text{mix}} = 1.744$$

Porosity was measured by conducting a series of tests with different size graduated cylinders. A report about the procedure was written and is available.

Both water and cuttings tests have been completed and the test matrix and results are as follows:

	Densitometer #1(downstream)				Densitometer #2(upstream)			
	RAW COUNTS	Calculated SpG	Measured SpG	SPAN	RAW COUNTS	Calculated SpG	Measured SpG	SPAN
100% air		0		0		0	0	
25% water	40608	0.25	0.337	33.68	39445	0.25	0.314	31.39
50% water	38798	0.5	0.518	51.81	37685	0.5	0.501	50.09
75% water	37210	0.75	0.676	67.61	36450	0.75	0.660	66.05
100% water		1	1.005	100.00	32463	1	1.006	100.00
25% cuttings & water	32000	1.248	1.235	100.00	31000	1.248	1.240	100.00
50% cuttings & water	30400	1.497	1.414	100.00	29770	1.497	1.390	100.00
75% cuttings & water	29290	1.744	1.579	100.00	28395	1.744	1.555	100.00

As we can see from the curve below, there are deviations between the calculated values based on physical measurements of water and cuttings versus the densitometer readings. A calibration curve is necessary to correct these differences.

Figure 6.2 – Calibration of a Nuclear Densitometer

Instability of a bed of particles sheared by viscous flow

When an initially flat bed of small heavy particles is sheared by a clear fluid, the bed is unstable and ripples grow. The existing stability analyses consider the resuspended layer as an effective Newtonian fluid whose viscosity and density depend on the local particle concentration. Zhang³, Acrivos & Schafliinger (1992) consider the particle as a well-mixed suspension with uniform particle concentration, so that the base flow is a two-layer plane Poiseuille flow. Accordingly, they discover the long- and short-wave instabilities due to the jump in viscosity discovered by Yih⁴ (1967) and Hopper⁵ & Boyd (1983), respectively.

The long-wave analysis of Loimer⁶ & Schafliinger (1998) introduces corrections of the viscosity and density with the interface height, which ensure mass conservation of the particles, and also includes a slip velocity of the suspended layer at the bottom wall. This improvement leads to an additional instability for small thicknesses of the less viscous clear fluid, which is not present in two-layer flows. In the studies of Zhang et al. and Loimer & Schafliinger, the assumption of uniform particle concentration implies a parabolic velocity profile with negative curvature in both layers, and a discontinuous slope of the velocity profile at the interface due to the viscosity jump. This assumption greatly simplifies the analysis and may be valid far from the threshold of particle movement (high Shields number) where the whole layer is resuspended. However, this assumption is not valid for smaller shear rates where the particle concentration varies continuously within the resuspended layer. Indeed, the effective viscosity gradient leads to a change of curvature of the velocity profile at the interface, which can be expected to affect the stability of the flow.

Miskin⁷, Elliott & Ingham (1999) take into account the velocity profile of the resuspended layer, as calculated by Schafliinger⁷ et al. (1990). However, the particle concentration is not perturbed in their study, which is a questionable assumption. Their analysis amounts to solving the Orr-Sommerfeld equation for channel flow, with given profiles for the basic streamfunction, density and viscosity. Long waves are found to be always unstable, with the striking result that the wave number $k = 0$ is generally unstable, and that it is the most unstable wave number for small Reynolds numbers. For completeness, it should be noted that the simulations by Stokesian dynamics of Morris⁸ & Brady (1998) do not report instabilities.

Francois Charru⁹ and Helene Mouilleron-Arnould investigated the the instability of a bed of particles sheared by a viscous fluid theoretically. In their paper, the viscous flow over the wavy bed is calculated, and the bed shear stress is derived. The particle transport rate induced by this bed shear stress is calculated from the viscous resuspension theory of Leighton¹⁰ & Acrivos (1986). Mass conservation of the particles then gives explicit expressions for the wave velocity and growth rate, which depend on four dimensionless parameters: the wave number, the fluid thickness, a viscous length and the shear stress. They suggest that for large enough fluid-layer thickness, long-wave instability arises as soon as grains move, while short waves are stabilized by gravity. For a smaller fluid thickness, the destabilizing effect of fluid inertia is reduced,

so that the moving flat bed is stable for small shear stresses, and unstable for high ones. They think the most amplified wavelength scales with the viscous length, in agreement with the few available experiments for small particle Reynolds numbers.

Figure 6.3 - Couette Flow over a Wavy Bed.

Figure 6.4 - Schematic of a Couette Resuspension Flow

FUTURE WORK

1. Develop a model to predict Non-Newtonian fluid/air two-phase flow behavior.
2. Continue to develop computer simulator for cuttings transport.
3. Continue the study of cuttings bed instability analysis.
4. Begin ACTS Flow-Loop tests.

DELIVERABLES

1. Semi-annual Advisory Board Meeting (ABM) reports.
2. Two-phase flow model for aerated fluids under elevated pressure and temperature conditions.
3. Practical guidelines and/or graphs to determine the optimum gas/liquid rate to get the maximum cuttings transport capacity of aerated fluids under elevated pressure and temperature conditions.
4. A computational tool to calculate frictional pressure drops inside an annulus for aerated fluids flowing over a range of experimental conditions.

Nomenclature

P = packed cuttings porosity

V_{tray} = volume of lower half of test section, cc

V_{upper} = volume of upper half of test section, cc

ρ_s = specific gravity of cuttings

ρ_w = specific gravity of water

ρ_{mix} = specific gravity of mixture

h = height of plane, m

γ = shear rate, 1/s

U = velocity, m/s

REFERENCES

1. R.D.Kaminsky,:" Predicting Single-Phase and Two-Phase Non-Newtonian Flow Behavior in Pipes," ASME vol.120 March,1998
2. Taitel , Y. and Dukler, A.E.:"A Model for Slug Frequency During Gas-Liquid Flow in Horizontal and Near Horizontal Pipes," Int. J. Multiphase Flow (1977)3, 585.
3. Zhang, K., Acrivos, A. & Shaflinger, U.:"Stability in a two-dimensional Hagen-Poiseuille resuspension flow." Intl J. Multiphase Flow,**18**, 51-63. 1992
4. Yih, C. S. : "Instability due to viscous stratification." J. Fluid Mech. **27**, 337-352,1967.
5. Hooper, A. P. & Boyd, W. G. C. : "Shear-flow instability at the interface between two viscous fluids." J. Fluid Mech. **128**, 507-528. 1983.
6. Loimer, T. & Schaflinger, U. "The effect of interfacial instabilities in a stratified resuspension flow on the pressure loss." Phys. Fluids **10**, 2737-2745. 1998
7. Miskin, I., Elliott, L. & Ingham, D. B. : "Stability in a fully-developed two-dimensional resuspension flow." Intl J. Multiphase Flow **25**, 501-530. 1999
8. Schaflinger, U., Acrivos, A. & Zhang, K. : "Viscous resuspension of a sediment within a laminar and stratified flow. "Intl J. Multiphase Flow **16**, 567-578. 1990
9. Morris, J. F. & Brady, J. F. "Pressure driven flow of a suspension: Buoyancy effects." Intl J. Multiphase Flow **24**, 105-130. 1998
10. Francois Charru and Helene Mouilleron-Arnould : "Instability of a bed of particles sheared by a viscous flow." J. Fluid Mech, vol.452, pp303-323 2002

7. DEVELOPMENT OF CUTTINGS MONITORING METHODOLOGY (Task 11)

Investigators: Kaveh Ashenayi and Gerald Kane (Profs Electrical Engr.)

Objectives

The ultimate objective of this task (Task 11) is to develop a non-invasive technique for quantitatively determining the location of cuttings in the annular (drilling) section of the ACTS Flow Loop. There are four different techniques that could be examined. However, as it was pointed out in the previous reports only three have good potential for success. These are Ultrasound, X-Ray/Gamma-Ray and Optical. Of these, we are concentrating on Ultrasound Transmitters and Sensors for Task 11.

Team Composition:

The team responsible for developing instrumentation to measure cuttings concentration and distribution within an annulus consists of Dr. Gerald R. Kane and Dr. Kaveh Ashenayi. Both are registered professional engineers and professors of Electrical Engineering Department at the University of Tulsa. MS level graduate students are assisting them. These students have BS degrees in EE and Computer Science. This particular combination works well since successful completion of this project requires skills from both disciplines. To achieve the objectives of this task, we will need to develop a very complicated electronic hardware/sensor and a software package that correctly interprets the ultra-sonic data received.

Progress to Date

The modifications of the PC board developed by our team have been completed. A new board is being produced. We have finalized our new set of commands to accommodate the new board. Also, we have tested the data averaging on board.

We have further developed PC software that will be used to collect and analyze data. The data collection part has been further revised and tested in conjunction with the new board. The software starts by allowing the user to setup the communication characteristics of the system. Then proceeds to identify the number of boards connected.

We have identified a set of software tools that will allow us to implement a neural network analysis package in this software.

Also, we conducted tests with solid plastic cap coverings over the transmitter/receiver sets. The objective was to determine if contact with solid matter blocks the signal. The results indicated that signal will be slightly attenuated, but it is still functional and useful.

Furthermore, we used a clear plastic test cell to conduct some preliminary tests. The objective was to use this test cell and visually verify the results obtained from the sensor

boards. The results indicate that we are able to see and distinguish between different concentrations of sand. Next step is to classify the shape.

Approach:

In subtask one of Task 11, we are to develop a static (followed by a dynamic) radial test cell and a preliminary set of instruments to detect the presence of cuttings in this cell.

The main approach being investigated is the ultrasound transmission versus reflected sound. We will investigate the need for an inner ring by comparing the results of two experiments. First, we will setup a set of rings in the outer pipe and a corresponding ring in the inner pipe. The inner ring will act as source and the outer ring will act as receivers. We will electronically rotate the angle at which the sound is being transmitted relative to the cuttings by switching from one sensor to another around the circumference of the outer pipe. We will measure the sound received, and compare it against sound transmitted. After suitable data processing, we believe it is possible to get an acceptable picture of what is inside the pipe. This is very similar to the MRI technique used by physicians.

In the second experiment, we will repeat the same experiment except we will not use the inner ring. If acceptable accuracy can be achieved with reflected sound this will eliminate the need for an inner ring. This, in turn, will make it much easier to use ultrasonics to measure cuttings concentration in the ACTS Flow Loop with rotation of a simulated drillpipe.

Future Work:

We are to test the new hardware and firmware. At the same time we are implementing our data analysis software.

Upon completion of these tests, we plan to use the clear plastic cell to conduct two sets of experiments. As described above, one set of tests will be with rings of transmitters/sensors mounted on both the outer pipe and the inner pipe. The inner ring will act as source and the outer ring will act as receivers. We will measure the sound received and compare it against sound transmitted. After suitable data processing, we believe it is possible to get an acceptable picture of what is inside the pipe and be able to quantify the distribution of cuttings concentration with an annular geometry.

In the second experiment we will repeat the same experiment, except we will not use the inner ring. In addition, we will use the same setup for calibrating the system.

We are currently planning to use neural networks to model effects of a slurry flow on the signal received as well as the shape of the sand collection. This is needed due to the

highly nonlinear nature of the flow. It has been shown that neural networks can successfully model nonlinear systems.

The dynamic testing will be designed and implemented. The small-scale experimental loop (Dynamic Testing Facility, see Section 8) will be used first before installing the system on the main Flow Loop. Steel pipes are used in both of these flow loops. Hence, it is anticipated that some changes will occur in the ultrasonic signals due to the different boundary conditions compared with the plastic cell. This will require some additional testing to compensate for this change in pipe materials. Then the developed system will be used for measurements of cuttings concentration in the dynamic case of a flowing slurry. In the DTF the fluid will be moving but no drilling action can be simulated. Whether an ultrasonic system can be used in the full-scale ACTS Flow Loop with rotation of a simulated drillpipe will depend on whether reflected sound can be use or not.

8. DEVELOPMENT OF A METHOD FOR CHARACTERIZING BUBBLES IN ENERGIZED FLUIDS (TASK 12)

Investigator: Leonard Volk (ACTS Research Associate)

8.1 Introduction

Bubbles (as foam or aerated fluid) will be moving at a high rate (up to 6 ft/sec) in the drilling section of the ACTF, and may be very small (down to 0.01 mm). The bubble size and size distribution influence the fluid rheology and the ability of the fluid to transport cuttings. Bubbles in a shear field (flowing) may tend to be ellipsoidal which might alter both the rheology and transport characteristics.

This project is Task 12 (Develop a Method for Characterizing Bubbles in Energized Fluids in the ACTF During Flow) in the Statement of Work, and is divided into four subtasks:

- Subtask 12.1. Develop/test a microphotographic method for static conditions
 - Subtask 12.2. Develop/test a method for dynamic conditions
 - Subtask 12.3. Develop simple, noninvasive methods for bubble characterization
 - Subtask 12.4. Provide technical assistance for installation on ACTF
- Subtask 12.1 includes (1) magnifying and capturing bubble images, (2) measuring bubble sizes and shapes, and (3) calculating the size distribution and various statistical parameters. Subtask 12.2 develops the methods needed to apply the results of Subtask 12.1 to rapidly moving fluids, especially the method of “freezing” the motion of the bubbles. A dynamic testing facility will be developed in conjunction with Task 11 for development and verification.
- Subtask 12.3, added in year 3, develops simple, inexpensive and small-in-size methods for characterizing bubbles. This task was previously referred to as “New Techniques”.
- Techniques and methods developed under Subtask 12.2 and 3 will be applied to the drilling section of the ACTF in Subtask 12.4.

8.2 Objective

The objective of this task is to develop the methodology and apparatus needed to measure the bubble size, size distribution and shape during cuttings-transport experiments.

8.3 Project Status

8.3.2 Dynamic Bubble Characterization

8.3.2.1 Dynamic Imaging

During this quarter, microscopic images were obtained of foam generated in a blender and the Dynamic Testing Facility (DTF). Foam from the blender was injected into our atmospheric visualization cell. Bubbles measured soon after injection (~ 1 minute 15 seconds) ranged from 60 μ m to 500 μ m. Foam generated in the DTF and flowed through the atmospheric visualization cell were as small as 40 μ m but a few were up to four times this size, after adjusting for the pressure drop. Bubble size depended on the shear rate (needle valve opening and flow rate). Whenever bubbles were examined with the visualization cell, the bubbles rapidly grew with time. Images of bubbles captured through the view port in the DTF circumvented this problem so long as the fluid passed through the needle valve. The bubble size varied between 25 μ m and

100 μ m at loop pressure, depending on the number of turns the needle valve was open and the flow rate.

At present, the platform holding the microscope and CCD camera are attached to the DTF superstructure. Minor vibrations are amplified considerably, causing some imaging problems. During the next quarter, we will be constructing a free-standing bench for the microscope and other optical methods that we are planning to use.

8.3.2.2 Dynamic Testing Facility

During this quarter a site glass constructed of 10mm diameter glass tubing and a millimeter scale was constructed to more accurately measure fluid volume introduced into the DTF from the mixing tank. An auxiliary drain was added ahead of the sump pump in order to speed up complete loop drainage. An additional support was installed under the chemical injection pump platform. The mixing manifold of the DTF was expanded to include a third leg incorporating the needle valve for better foam generation (more shear). The high-pressure clear-glass section for monitoring foam development and degradation and “Flexzorbers” for reducing torsional stress on this cell have been received.

The following are still needed:

- Construct a “turn indicator” for the shearing needle valve.
- Calibrate the nitrogen manifold needle valves.
- Mount an RPM indicator on the Moyno pump shaft and calibrate it for better flow measurements.
- Check out the operation of the chemical injection pump
- Design/install a Lexan shield for the clear-glass section

8.3.3 Novel Techniques for Bubble Characterization

Average bubble size. The optical transmission of blender-generated foam was measured in four cells having path lengths ranging from ½” to ~6”. Rapid degradation of foam prevented quantitative measurements on static foam, but transmitted light intensity decreased markedly as the path length increased. Transmitted light intensity also increased as the average bubble size increased. Quantitative measurement of the transmitted light intensity will either require the addition of a foam stabilizer or measurement under dynamic conditions.

Foam Quality. The light intensity reflected off a foam-glass interface was intermediate to the light intensity reflected off a water-glass interface and an air-glass interface. Quantitative measurements to determine foam quality will require better foam stability or measurement of dynamic foam. The current light source, a He-Ne laser, has an average beam diameter of about 800 micrometers. So far the bubble sizes are considerably smaller than this, which is required for stable measurement and determination of foam quality. Other, much more compact lasers exist with beam diameters up to 3 mm if needed.

Foam stability from blender tests and foam generated within the DTF loop suggest that the foam bubble size and quality (top-of-pipe compared to bottom-of-pipe) will change as the foam moves away from the high-shear foam generation source. Therefore, brass fittings, small windows and

a small equilateral prism have been ordered to begin construction of prototype devices for measuring the mean bubble size and foam quality.

8.4 Planned Activities

8.4.1 Dynamic Bubble Characterization

- Construct a “turn indicator” for the shearing needle valve.
- Calibrate nitrogen manifold needle valves.
- Mount an RPM indicator on the Moyno pump shaft and calibrate for better measurement of flow.
- Check out operation of chemical injection pump.
- Construct/install a Lexan shield for the clear glass section.
- Construct a stable platform for mounting the microscope and optics to minimize the effect of vibration.
- Using the imaging instrumentation and software, develop a routine for bubble analysis.

8.4.2 Novel Techniques for Bubble Characterization

- Set up optics near the DTF for measuring average bubble size and foam quality.
- Design/construct prototype devices for measuring average bubble size and foam quality.

9. SAFETY PROGRAM (TASK 1S)

Chairman, Process Hazards Review Team: Leonard Volk (ACTS R.A.)

9.1 Introduction

This project was initiated during the fourth quarter of 2000 to assess the hazards associated with the Advanced Cuttings Transport Facility (ACTF) and develop an Action Plan to address problems discovered during this Hazards Review. A Hazards Review is an industry accepted method used to improve the overall safety characteristics and reduce the possibilities of accidents in the work place. Each individual component of the ACTF is examined as to the effect and consequences on safety, health, and the environment, of the component in all possible operational modes. A Hazards Review can result in equipment modification, inspection and testing, documentation, personal protective equipment, personnel training, and/or emergency training.

The hazards review process begins by selecting a review method. Next a team of qualified individuals must be formed. This team should include those knowledgeable in the review process and those familiar with the process to be reviewed. Prior to beginning the review, all available documentation needs to be gathered. This includes schematics, organized training, periodic inspections and testing results, design and construction documents, operating procedures, etc. Once the schematics have been verified and the operator of the equipment or process has reviewed its operation with the team, the Hazards Review begins. The review should continue uninterrupted until completed. After the findings and recommendations have been completed, a draft report is issued and reviewed by all team members, and the operator of the process or equipment.

Following this review, any changes are incorporated and a final report issued. This completes the Hazard Review process. The operator then needs to develop an action plan to implement the recommendations from the Hazard Review. In our case, team members will participate in developing this plan.

9.2 Objectives

The objective of this task is to identify problems (findings) that might result in injury, property damage or the release of environmentally damaging materials and provide recommendations to minimize them, and to develop an action plan based on these recommendations.

9.3 Project Status

Activities this quarter have continued to center on implementing the Action Plan and addressing several findings listed in the Hazard Review as well as preparing for the May 2002 Advisory Board Meeting.

9.4 Planned Activities

- Continue implementation of the Action Plan.
- Prepare for review of latest modifications to the ACTF.
- Begin designing and preparation of a safety training class.

10. TECHNOLOGY TRANSFER

Meetings with Petroleum and Service Companies

ExxonMobil attended the May ABM and subsequently indicated an interest in joining the TU's JIP Projects. In addition, a visit was made to the Houston headquarters of MI Drilling Fluids. During this visit a presentation was made on the ACTS Project. The response from MI was very positive, and they have also indicated an interest in joining the ACTS Project.

Unfortunately, the merger between Conoco and Phillips has caused them to delay a decision about participating in the TU JIP Projects. Since the merged companies will become the third largest petroleum company in the US, we will continue to be alert for the right timing to reinstate our efforts to attract the new ConocoPhillips. In the mean time, we will continue to identify and contact other petroleum and service companies that will benefit by participating in this project.

ACTS-JIP Advisory Board Meeting

The next Advisory Board Meeting will be held on November 19, 2002. In addition to the DOE, there are currently 10 member companies participating in the ACTS-JIP Project. They are: 1) British Petroleum, 2) Baker-Hughes, 3) ChevronTexaco, 4) Schlumberger Dowell, 5) Halliburton, 6) Intevep, 7) Petrobras, 8) Statoil, 9) TotalFina-Elf, and 10) Weatherford International.

Membership of the Japanese National Oil Co. expired at the end of Year-3 (July 13, 02).