DOE/BC/15178-1

Title: Advanced Cuttings Transport Study

Type of Report: Quarterly
Reporting Period Start Date: July 1, 2001
Reporting Period End Date: Sept. 30, 2001

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Date of Issue: Oct. 30, 2001
DOE Award Number: DE-FG26-99BC15178

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1. SUMMARY OF CURRENT TASKS FOR ACTS PROJECT

This is the first quarterly progress report for Year 3 of the ACTS project. It includes a review of progress made in: 1) Flow Loop development and 2) research tasks during the period of time between June 30, 2001 and Sept. 30, 2001.

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

a) Design and development of an Advanced Cuttings Transport Facility
(**Task 2**: Addition of a foam generation and breaker system and
Task 3: Addition of a Cuttings Injection/Collection System),

b) Research project (**Task 6**): " Study of Cuttings Transport with Foam Under LPAT Conditions (Joint Project with TUDRP)",

c) Research project (**Task 9**): " 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 instrumentation tasks to measure:
- Cuttings concentration and distribution in a flowing slurry (**Task 11**), and
- Foam properties while transporting cuttings. (**Task 12**),

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 2 & Task 3)**
Construction and development of the flow loop is continuing. During this quarter, installation of the air/foam system was completed. Generation of foams with a controllable gas/liquid ratio (quality) was achieved according to the design plan. However some problems were initially encountered with controlling back pressure on the flow loop. It was learned that additional programming of the LabView software was necessary in order to vary the gain on the vent valve at the top of the breaker or separation tower. In addition, some difficulties were encountered in breaking the foam at the separation tower. The primary cause of the problem was traced to a faulty pump that injects breaker chemical into the flowing foam. After correcting this pump problem, foam is now being broken and separated into air and water without any problem. Task 9 tests were started during this quarter and will continue into the fall.

Efforts continued on the design of a Cuttings Injection/Collection System (**Task 3**). This is the primary construction task during Year-3. It is anticipated that the design will be submitted to qualified contractors sometime during the fall, 2001. 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**).
A solution for the set of 7 equations (2 mass balance, 3 momentum balance, 1 slip velocity between cuttings and fluid in layer 2, 1 cuttings concentration distribution in layer 2) describing the cuttings transport phenomena as a layered model, and 7 unknowns (velocity of fluid at layer 1 and 2, slip velocity in layer 2, cuttings concentration in layer 2, cuttings bed area, flow area of layer 2, pressure drop) was develop. The cuttings transport experiments by using foam in horizontal and inclined wellbore cases were conducted, and preliminary analysis of the experimental data was completed. Also, a general equation was developed for determining the bed thickness in the wellbore. Some of the details are presented in Section 4.

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

The final configuration of the test matrix is reported. Data analysis continues, and some results are reported and discussed. A new effect on rheological behavior of foams, related to the way foam is generated, was investigated. This effect encouraged the extension of the test matrix, and a new set of tests were performed. A preliminary discussion of the impact of the new foam generation on hydraulic behavior is presented in Section 5 of this report.

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

Literature review on related knowledge and study the previous works done by TUDRP/ACTS are still continuing. Mathematical models are being development. Theoretical analysis of cuttings transport phenomena based on layered models is under development. Slug flow analysis is continuing. Measurements of Slug

frequency, slug velocity and slug length by using nuclear densitometer is under investigation. Experiments are being planned to investigate the flow behavior of aerated mud under elevated pressure and temperature conditions. A test matrix has been designed.

Research on Instrumentation to Measure Cuttings Concentration and Distribution in a Flowing Slurry, (**Task 11**).
Work is continuing on the development of an ultrasonic instrumentation to measure cuttings concentration and distribution within an annular geometry. Circuit boards have been designed to control the sequencing of sound emitted by transmitters mounted on the inner pipe and sound that passes through the cuttings and is received by sensors on the circumference of the outer pipe. In addition, software is being developed to process the data and enable transmitted sound to be related to cuttings concentration. This task is reviewed in Section 7.

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

Leaking, defective flanges have prevented pressurized foam testing with the lab-scale flow loop for dynamic foam characterization and cuttings monitoring instrumentation development. All 22 flanges have been replaced. Several auxiliary systems have been completed. The status of this work is reviewed in Section 8.

Safety Program for the ACTS Flow Loop, **(Task 1S)**
The draft report of the Hazards Review has been completed and submitted to the Work Team for their input. Once their suggestions have been incorporated, the report will be reviewed by the Review Team. Next action includes completion of the Action Plan to address the findings identified by the Hazards Review. 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 next ACTS-JIP Advisory Board Meeting is scheduled for November 13, 2001. Conoco and Phillips will be invited to attend. We continue to expect that Conoco will join in the near future. In addition, we are continuing to make new contacts with other companies in the Petroleum Industry in our search for additional JIP members. Further discussion of these activities is given in Section 10.

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3. ACTF DESIGN AND CONSTRUCTION ACCOMPLISHMENTS

3.1 Construction – July 1 through Sept. 30, 2001

The primary activity for this quarter has been conducting foam tests. These have tests have proven that the overall system for generating foam, measurements of frictional pressure drops, and then the breaking of foam and the separation of gas and liquid components works very well. Some refinements were made to the controlling LabView software in order to reduce pressure fluctuations in the Separation Tower. Foam tests at pressures up to 650 psi gauge and temperatures of 185 F are being conducted. Some of the test data is discussed in Section 5 of this report.

Design activity has continued for Year-3 tasks. Designs for a Cuttings Injection Hopper and a Cuttings Removal Tower have been completed and contractor bids will be solicited in the near future. Additional supplementary equipment such as a Johnson Screen, an Auger for the Injection Hopper, a loading elevator, a drilling choke, and related piping additions and electrical components will be ordered during the next two quarters. It is currently expected that this new system will be installed by March 1, 2002. and the commissioning process will begin then.

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 (numerically) frictional pressure losses (with and without cuttings) and volumetric requirements (injection rate, injection pressure and back-pressure) for effective cuttings transport with foam flow in inclined and horizontal wellbores.

PROJECT STATUS

- Layered cuttings transport model is developed. A set of 7 equations (2 mass balance, 3 momentum balance, 1 slip velocity between cuttings and fluid in layer 2, 1 cuttings concentration distribution in layer 2) and 7 unknowns (velocity of fluid at layers 1 and 2, slip velocity in layer 2, cuttings concentration in layer 2, cuttings bed area, area of layer 2, and pressure drop) is developed.
- Experiments on cuttings transport with foam for horizontal and high-inclined wellbores are conducted. Preliminary analysis of the experimental data is completed.
- An equation for determination of bed thickness in the wellbore is developed.

FUTURE WORK

Experiments on cuttings transport with foam will be completed. A computer program will be developed by using the concepts of a layered model, and the results will be compared with experimental data.

WORK DONE

Literature Survey	Rheology of Foam	95%
	Cuttings Transport Phenomena	95%
Modification of Loop for Foam Flow	Plan	99%
	Construction	99%
Experiments Performed	Foam without Cuttings	90%
	Foam with Cuttings	80%
Model Developed	Rheology Review	95%
	Cuttings Effect	95%
Computer Simulator	Without Cuttings	90%
	With Cuttings	50%

LAYERED CUTTINGS TRANSPORT MODEL

A layered wellbore section with length ΔL, inclination α, and a pressure difference between the inlet and outlet of the section ΔP, is presented as shown in Figure 4.1. The following equations are derived under the assumptions that, the fluid within ΔL is incompressible and fluid properties are constant, cuttings bed is stationary and flow is ignored inside the bed, flow is steady. Detailed explanations can be found in the first quarterly DOE Progress Report for Year-2, October 30, 2000.

Mass Conservation

Assuming a constant ROP and flow rate, the material balance for fluid and solid phases can be written as

$$\upsilon_I A_I \rho_f + \upsilon_{II_f} A_{II} \rho_f \left(1 - C_{C_{II}}\right) = \bar{\upsilon} A_w (1 - C_C) \rho_f$$

$$\upsilon_t A_{II} C_{C_{II}} \rho_c = \bar{\upsilon} A_w C_C \rho_c$$

where

$$\upsilon_t = \upsilon_{II_f} - \upsilon_{slip}$$

Momentum Conservation

Conservation of linear momentum is defined as

$$\sum \vec{F} = \iint_{CS} \rho \vec{\upsilon} \left(\vec{\upsilon}.\vec{n}\right) dA + \frac{\partial}{\partial t} \iiint_{CV} \rho \vec{\upsilon} dV$$

For steady state conditions, the second term on the right is zero. By using Figure 4.1, the momentum conservation within the wellbore for layer-I, layer-II and layer-III, respectively, can be derived as

$$\Delta P A_I - \tau_{I-II} S_{I-II} \Delta L - \tau_{I-w} S_{I-w} \Delta L - \rho_f g A_I \Delta L Sin\alpha = \rho_f A_I \upsilon_I^2$$

$$\Delta P A_{II} + \tau_{I-II} S_{I-II} \Delta L - \tau_{II-III} S_{II-III} \Delta L - \tau_{II-w} S_{II-w} \Delta L - \rho_s g A_{II} \Delta L Sin\alpha$$
$$- \rho_f g A_I \Delta L Sin\alpha = \rho_s A_{II} \upsilon_{II}^2$$

$$\Delta P A_{III} + \tau_{II-III} S_{II-III} \Delta L - \mu_{static} \rho_{bed} g A_{III} \Delta L Cos\alpha - \rho_s g A_{II} \Delta L Sin\alpha$$
$$- \rho_f g A_I \Delta L Sin\alpha = 0$$

The shear stress between any two surfaces is

$$\tau_{i,j} = f_{f_{i,j}} \frac{\rho_i \left(\upsilon_i - \upsilon_j\right)^2}{2}$$

Slip Velocity

A slip velocity definition was presented in quarterly DOE Progress Report, dated April 30, 2001. The following equation is derived by modeling the moment of a particle about point *P*, which lies on the cuttings bed as shown in Figure 4.2.

The slip velocity between the fluid and cuttings in layer-II can be derived as

$$\upsilon_{slip} = \sqrt{\left(\frac{4}{3}\frac{d_c\,\bar{g}}{\left(C_L Sin\,\beta + C_D Sin\,\theta\right)}\right)\left(\frac{\rho_c - \rho_f}{\rho_f}\left(Cos\,\alpha\,Sin\,\beta + Sin\,\alpha\,Sin\,\theta\right)\right)}$$

where β is the angle ACP, and θ is the angle OCP in Figure 4.2. When the wellbore is in a vertical position, (α=90, β=0, θ=90 (cubic packing)), the equation reduces to Stokes' law. For the horizontal case, β=30, θ=35. A detailed derivation is presented in the Appendix attached to this report.

In-Situ Cuttings Concentration

Determination of the in-situ concentration of the cuttings at layer-II is very important for defining the mixture density at layer-II accurately. By using the equation of continuity, in-situ cuttings concentration at layer-II can be derived as

$$C_{C_{II}} = \frac{2\mathbb{N}_C^{\,2}\left(C_{C_{bottom}} - C_{C_{top}}\right) + C_{C_{top}}\mathbb{N}_C h_{II}^{\,2}\upsilon_y^{\,2} - \dfrac{\left(C_{C_{bottom}} - C_{C_{top}}\right)h_{II}\upsilon_y\left(2\mathbb{N}_C + h_{II}\upsilon_y\right)}{e^{\frac{h_{II}\upsilon_y}{\mathbb{N}_C}} - 1}}{h_{II}^{\,2}\upsilon_y^{\,2}}$$

where[1]

$$\mathbb{N}_C = -\frac{d_c^{\,2}}{4}\frac{\partial\upsilon}{\partial y}\left(0.43\,C_{C_{II}} + 2.04\,C_{C_{II}}^{\,2}\frac{1}{\left(1 - \dfrac{C_{C_{II}}}{C_{C_{bed}}}\right)}\right)$$

The detailed derivation is presented in the Appendix.

Friction on the Cuttings Bed

Friction on a cuttings bed has been studied by several researchers. The suggested[2-3] equation for determining the friction on a cuttings bed is

$$\frac{1}{\sqrt{2f_f}} = -0.86\ln\left(\frac{\dfrac{d_c}{D_h}}{3.7} + \frac{2.51}{N_{\mathrm{Re}}\sqrt{2f_f}}\right)$$

Friction between Layer-I and Layer-II

For determining the friction between layer-I and layer-II, the same equation for friction on bed can be used, if d_c is replaced by a characteristic diameter

$$d_{ch} = d_c\sqrt[3]{\frac{C_{C_{II}}}{C_{C_{\max}}}}$$

If the in-situ cuttings concentration is equal to the maximum cuttings concentration (this means a cuttings bed), d_{ch}.becomes equal to d_c and the

equation reduces to the friction factor equation for the bed surface. If the in-situ cuttings concentration goes to 0, d_{ch} becomes 0, and the friction factor equation reduces to the basic friction factor equation for a fluid flowing in a smooth pipe.

Angle of Repose

A set of laboratory experiments was conducted for the determination of the angle of repose of the cuttings used in TUDRP-LPAT Flow Loop.

Dry cuttings were deposited on a smooth horizontal surface, and the angle of repose was determined by measuring the dimensions of the cone developed by the cuttings. The angle of repose of the cuttings was found to be approximately 29 degrees.

Linearization of the Layered Model

The equations presented above are non-linear equations. In order to solve the equations numerically, a linearization process is required.

The linearization is conducted by using iterative expansion. The non-linear terms are represented by their previous and present values. A detailed explanation is given in the Appendix.

After linearization, a matrix is formed, and the unknowns are determined by using the implicit method for guaranteeing the convergence of the system of equations.

CUTTINGS BED AREA DETERMINATION

Thickness of the cuttings bed is one of the most essential information required for controlling the hole cleaning performance for a successful drilling operation. As described in quarterly DOE Progress Report, April 30, 2001, there are several independent drilling variables that control the development of a cuttings bed in a wellbore. These variables include inclination angle, feed cuttings concentration, fluid density, fluid viscosity, average fluid velocity and wellbore geometry.

Dimensional Analysis

As presented in the Appendix, a dimensional analysis is conducted by using those independent variables, and four dimensionless groups are developed; inclination, cuttings concentration, Reynolds number and Froude number. Thus, the dimensionless bed area can be described as a function of those dimensionless groups as

$$\frac{A_{bed}}{A_w} = f\left(C_C, \theta, N_{\mathrm{Re}}, N_{Fr}\right)$$

General Form

A possible relation among these dimensionless groups may be the multiplication form. Thus, a general representation of the dimensionless bed area may be

$$\frac{A_{bed}}{A_w} = k_1 \left(C_C\right)^{k_2} \left(\theta\right)^{k_3} \left(N_{\mathrm{Re}}\right)^{k_4} \left(N_{Fr}\right)^{k_5}$$

EXPERIMENTAL SECTION

The cuttings transport experiments were conducted by using TUDRP's LPAT Flow Loop. During the experiments, liquid and gas flow rates, inlet pressure, fluid temperature, differential pressure in the test section, cuttings tank weight measurements and inclination are recorded by using a computerized data-acquisition system.

Water-Cuttings Experiments

Experiments with water were conducted for 70, 80 and 90 degrees inclinations with flow rate ranging from 100 to 500 gpm and a varying rate of penetration of 30 to 60 ft/hr.

Foam-Cuttings Experiments

Experiments with foam were conducted for 70%, 80% and 90% foam quality, inclinations ranging from 70 to 90 degrees with a range of average annular flow velocities of 2 ft/sec to 16 ft/sec and with a rate of penetration varying from 20 to 60 ft/hr.

In both water and foam experiments, a decrease in the cuttings bed area and an increase in frictional pressure drop is observed with increasing flow rate. The experimental results are discussed in Results and Discussions section.

Friction Between Cuttings Bed and Wellbore

A set of lab experiments was conducted for determination of the friction factor between the cuttings bed and wellbore. Since TUDRP-LAPT Flow Loop has an acrylic casing, the lab experiments were conducted by using several acrylic pipes with inner diameters of 0.5 in., 1 in. (which represent the pipes), 2 in. and 3 in. (which represent the wellbores) and the same cuttings that are used in the flow loop. The pipes were filled with various amounts of cuttings. Beginning from the horizontal position, the pipes were elevated with one end fixed. The inclination angle was recorded as soon as the bed started to move. The tangent of the recorded angle is the friction coefficient between the bed and the acrylic pipe.

After the analysis of the results, the following relation was obtained

$$\mu_{static} = 0.617\left(\frac{A_{bed}}{A_w}\right)^{0.2518}$$

RESULTS AND DISCUSSIONS

Cuttings Transport Performance

Unlike in vertical wells, performance of foam in cuttings transport in horizontal wells is not promising. Experiments showed that foam could transport cuttings without developing a thick cuttings bed only at very high velocities, i.e. average annular velocity of 15 ft/sec. Since foam has a high viscosity, it cannot create enough turbulence to pick the cuttings up from the surface of the cuttings bed. When the velocity is increased, the lift force acting on the cuttings on the bed surface also increases, thus, cuttings can be pulled up from the bed surface, and due to the high drag force, they are carried away in the flow direction.

Pressure Drop Information

When cuttings are introduced into the test section, an increase in the pressure drop is observed. Figures 4.3 and 4.4, comparison of foam with and without cuttings for 80% and 90% quality as a function of Reynolds number and Froude number respectively, show that cuttings cause an increase in frictional pressure losses although flow conditions are kept constant.

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Relations with Cuttings Bed Area

As mentioned in the theory section, the cuttings bed is defined by a function of four independent dimensionless groups. By using the experimental data, the relation among each independent group and the bed thickness is analyzed.

Inclination

No significant change in cuttings bed thickness is observed when the inclination of the wellbore is varied from 70 to 90 degrees regardless of the flow rate and rate of penetration with both water and foam. Figures 4.5 to 4.7 show the slight effect of inclination on cuttings bed area with varying cuttings concentration, Reynolds number and Froude number, respectively.

Cuttings Concentration

The relation between the cuttings concentration and bed thickness is plotted in Figure 4.8 for water and Figure 4.9 for foam. As seen from these figures, an increase in bed thickness is observed when the cuttings concentration increases.

Reynolds Number

In Figures 4.10 and 4.11, the relation between the Reynolds number and bed area is presented for water and foam respectively. A higher Reynolds number leads to the development of a smaller cuttings bed in the wellbore.

Froude Number

Higher Froude number means the inertial forces are dominant. As presented in Figures 4.12 and 4.13, cuttings bed thickness decreases with increasing Froude number for both water and foam.

GENERALIZED CUTTINGS BED AREA EQUATION

After observing the similarities between the analysis results of water and foam, a combined analysis was conducted for determining a general bed area relation valid for a wide range of fluids used in the drilling industry. Besides water and foam data, additional bed thickness information was included by using the data of a polymer based mud used in TUDRP-LPAT Flow Loop. Therefore, a database was developed for different drilling fluids and their cuttings transfer performances.

Statistica® was used for developing the dimensionless bed area equation constants as in the multiplication form. After inserting the constants, the equation looks like

$$\frac{A_{bed}}{A_w} = 0.941\left(\left(C_C\right)^{-0.0347}\left(N_{\mathrm{Re}}\right)^{-0.0827}\left(N_{Fr}\right)^{-0.1708}\right)$$

Inclination is excluded from the equation since no significant effect of inclination angle was observed on cuttings bed thickness over the range of 70 to 90 degrees.

In Figure 4.14, experimental data was compared with a dimensionless bed area equation developed by using various combinations of the fluids, including water, foam and polymer. As seen from the figure, all the equations estimate almost the same results. Thus, such an equation presented above should give accurate information about the status of the cuttings bed present in the wellbore under any given drilling conditions.

Figure 4.15 gives a good idea about the accuracy of the equation. In this figure, the residual error is presented. As seen in the figure, the maximum error is 20%.

COMPUTER SIMULATOR

Based on the layered model described above, a computer simulator is under construction. The program will able to determine the seven unknowns by using as inputs flow rate, ROP, wellbore geometry, inclination, inlet pressure and temperature, and rheological properties of the fluid. Results from the computer model will be tested by comparing with experimental data, as soon as the program is completed.

CONCLUSIONS & REMARKS

At this stage of the project, the following remarks and conclusions can be made:

1. Cuttings transport performance of foam in horizontal wells is not as promising as in vertical wells. High annular velocities of foam are required to transport cuttings without having a thick bed in the wellbore.
2. Presence of cuttings significantly increases the frictional pressure losses in the wellbore.
3. Cuttings transport performance is slightly affected by variation of wellbore inclination (70-90 degrees)
4. A general equation can be defined for estimating the cuttings bed area under given drilling conditions.

NOMENCLATURE

A = area, L^2
C = cuttings concentration
C_D = drag coefficient
C_L = lift coefficient
D= diameter, L
d = diameter, L
f_f = friction factor
g = gravitational constant, L/t^2
h = height, L
k = constant
L = length, L
Í $_C$ = diffusion coefficient
N_{Fr} = Froude number

N_{Re} = Reynolds number
P = pressure, m/Lt^2
S = surface

Greek Letters

β = angle
θ = angle
ρ = density, m/L^3
α = inclination
τ = shear stress
υ = velocity, L/t

Subscripts

c = cuttings
ch = characteristic
f = fluid
I = first layer
II = second layer
III = third layer
i = layer index
j = layer index
s = slurry
w = wellbore
y = direction

ACKNOWLEDGEMENTS
TUDRP and the author thank Bachman Chemicals for donating foaming agent and foam breaker.

APPENDIX

Mathematical Derivations

The following section contains the derivations referred to in the report.

Derivation of Slip Velocity

The force balance of the system shown in Figure 4.2 is

$$\left(F_D + \left(F_b - W\right) Sin\,\alpha\right)\frac{d_c}{2} Sin\,\theta + \left(F_L + \left(F_b - W\right) Cos\,\alpha\right)\frac{d_c}{2} Sin\,\beta = 0$$

where the weight of the particle is

$$W = \frac{\pi}{6} d_c^3\, \rho_c\, \vec{g}$$

Drag and Lift forces are defined, respectively, as

$$F_D = \frac{1}{2} C_D \frac{\pi}{4} d_c^2\, \rho_f\, \upsilon^2$$

$$F_L = \frac{1}{2} C_L \frac{\pi}{4} d_c^2\, \rho_f\, \upsilon^2$$

Buoyancy force can be expressed as

$$F_b = \frac{\pi}{6} d_c^3\, \rho_f\, \vec{g}$$

Inserting these equations into the governing equation and solving for the velocity yields

$$\upsilon_{slip} = \sqrt{\left(\frac{4}{3}\frac{d_c\, \vec{g}}{\left(C_L Sin\,\beta + C_D Sin\,\theta\right)}\right)\left(\frac{\rho_c - \rho_f}{\rho_f}\left(Cos\,\alpha\, Sin\,\beta + Sin\,\alpha\, Sin\,\theta\right)\right)}$$

Derivation of In-Situ Cuttings Concentration

Assuming a rectangular coordinate system for simplicity, the equation of continuity can be written as

$$\frac{\partial C}{\partial t} + \left(\upsilon_x \frac{\partial C}{\partial x} + \upsilon_y \frac{\partial C}{\partial y} + \upsilon_z \frac{\partial C}{\partial z}\right) = \mathbb{N}_C \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

Let $\frac{\partial C}{\partial x} = \frac{\partial C}{\partial z} = 0$, $\frac{\partial C}{\partial t} = 0$, density and diffusion coefficient is constant. Thus, the continuity equation becomes

$$\upsilon_y \frac{\partial C}{\partial y} = \mathbb{N}_C \frac{\partial^2 C}{\partial y^2}$$

where

$$\upsilon_y = \upsilon_{ter} Cos\alpha$$

From Stokes' Law

$$\upsilon_{ter} = \sqrt{\frac{4}{3}\frac{d_c \bar{g}}{C_D}\left(\frac{\rho_c - \rho_f}{\rho_f}\right)}$$

The boundary conditions for the second order differential equation is

$$y = 0,\ C_C = C_{C_{bottom}}$$
$$y = h_{II},\ C_C = C_{C_{top}}$$

Thus, solution of this second order differential equation gives

$$C_C(y) = \frac{-C_{C_{bottom}} + C_{C_{top}} e^{\frac{h_{II}\upsilon_y}{\mathbb{N}_C}} + \left(C_{C_{bottom}} - C_{C_{top}}\right) e^{\frac{\upsilon_y (h_{II} - y)}{\mathbb{N}_C}}}{e^{\frac{h_{II}\upsilon_y}{\mathbb{N}_C}} - 1}$$

The average cuttings concentration in layer-II can be determined by integration of $C_C(y)$ over the thickness of layer-II

$$C_{C_{II}} = \frac{\int_0^{h_{II}} \left(\frac{-C_{C_{bottom}} + C_{C_{top}} e^{\frac{h_{II}\upsilon_y}{\mathbb{N}_C}} + \left(C_{C_{bottom}} - C_{C_{top}}\right) e^{\frac{\upsilon_y (h_{II} - y)}{\mathbb{N}_C}}}{e^{\frac{h_{II}\upsilon_y}{\mathbb{N}_C}} - 1} \right) y\,dy}{\int_0^{h_{II}} y\,dy}$$

which gives

$$C_{C_{II}} = \frac{2\mathbb{N}_C^{\,2}\left(C_{C_{bottom}} - C_{C_{top}}\right) + C_{C_{top}}\mathbb{N}_C h_{II}^{\,2}\upsilon_y^{\,2} - \frac{\left(C_{C_{bottom}} - C_{C_{top}}\right) h_{II}\upsilon_y \left(2\mathbb{N}_C + h_{II}\upsilon_y\right)}{e^{\frac{h_{II}\upsilon_y}{\mathbb{N}_C}} - 1}}{h_{II}^{\,2}\upsilon_y^{\,2}}$$

$\mathbb{N}_C$ is defined as

$$\mathbb{N}_C = -\mathbb{N}_{C_{concentration}} - \mathbb{N}_{C_{shear\ stress}} \left(\frac{\frac{\partial^2 \upsilon}{\partial y^2}}{\frac{\partial C_C}{\partial y}} \right)$$

Assuming a linear velocity profile (h_{II} is small)

$$\mathbb{N}_C = -\mathbb{N}_{C_{concentration}}$$

Thus

$$\mathbb{N}_C = -\frac{d_c^{\,2}}{4}\frac{\partial \upsilon}{\partial y}\left(0.43\,C_{C_{II}} + 2.04\,C_{C_{II}}{}^{2}\frac{1}{\left(1-\dfrac{C_{C_{II}}}{C_{C_{bed}}}\right)}\right)$$

At $y = 0, \upsilon = \upsilon_{slipbed}$ and at $y = h_{II}, \upsilon = \upsilon_I$ Therefore,

$$\frac{\partial \upsilon}{\partial y} = \frac{\upsilon_I - \upsilon_{slipbed}}{h_{II}}$$

Dimensional Analysis for Cuttings Bed Area

In order to make a dimensional analysis, a matrix is developed by using the independent variables and the basic units.

	C_C	θ	$\frac{A_{bed}}{A_w}$	ρ	$\bar{g}$	μ	υ	D
m	0	0	0	1	0	1	0	0
L	0	0	0	−3	1	−1	1	1
t	0	0	0	0	−2	−1	−1	0
π_1	1	0	0	0	0	0	0	0
π_2	0	1	0	0	0	0	0	0
π_3	0	0	1	0	0	0	0	0
π_4	0	0	0	1	0	−1	1	1
π_5	0	0	0	0	1	0	−2	1

As seen from the matrix, the difference between the number of independent variables and the units is 5. Thus, there should be 5 dimensionless groups, including dimensionless bed area. The numbers on the rows of dimensionless groups show the relation between the independent variables and the dimensionless groups. Therefore, the dimensionless groups can be defined as

$$\pi_1 = C_C$$

$$\pi_2 = \theta$$

$$\pi_3 = \frac{A_{bed}}{A_w}$$

$$\pi_4 = \frac{\rho \upsilon D}{\mu} = N_{\mathrm{Re}}$$

$$\pi_5 = \frac{\bar{g}\,D}{\upsilon^2} = \frac{1}{N_{Fr}}$$

Thus, the equation becomes

$$\frac{A_{bed}}{A_w} = f\left(C_C, \theta, N_{\mathrm{Re}}, N_{Fr}\right)$$

The detailed explanation of the diameter definition used in Reynolds number and Froude number is in ABM Progress Report, May 2001.

Linearization of the Non-Linear Equations

Suppose an equation has a term x^2 and iteration has to be performed. The non-linear term can be linearized by splitting the non-linear term, and using the previous iteration value and the new value together in the same equation. Thus,

$$x^2 = x_{n+1}\, x_n$$

where n is the iteration number. Since x_n is already known, it is a constant; therefore, x^2 is linearized. In a set of equations, i.e.

$$\begin{aligned}
a_{11}\, x_1 + a_{12}\, x_2 + \cdots + a_{1n}\, x_n &= a_{1,n+1} \\
a_{21}\, x_1 + a_{22}\, x_2 + \cdots + a_{2n}\, x_n &= a_{2,n+1} \\
\vdots \qquad\qquad\qquad\qquad \vdots \qquad &\quad \vdots \\
a_{n1}\, x_1 + a_{n2}\, x_2 + \cdots + a_{nn}\, x_n &= a_{n,n+1}
\end{aligned}$$

Thus, the algorithm can be described as

$$x_{i,k+1} = a_{i,n+1} - \sum_{j=1}^{i-1} a_{ij}\, x_{j,k+1} - \sum_{j=i+1}^{n} a_{ij}\, x_{j,k}$$

where

$$i = 1, 2, \ldots, n$$

Also, an implicit method can be applied rather than an iterative approach, and the matrix can be solved by using a matrix solver; i.e., Gauss elimination.

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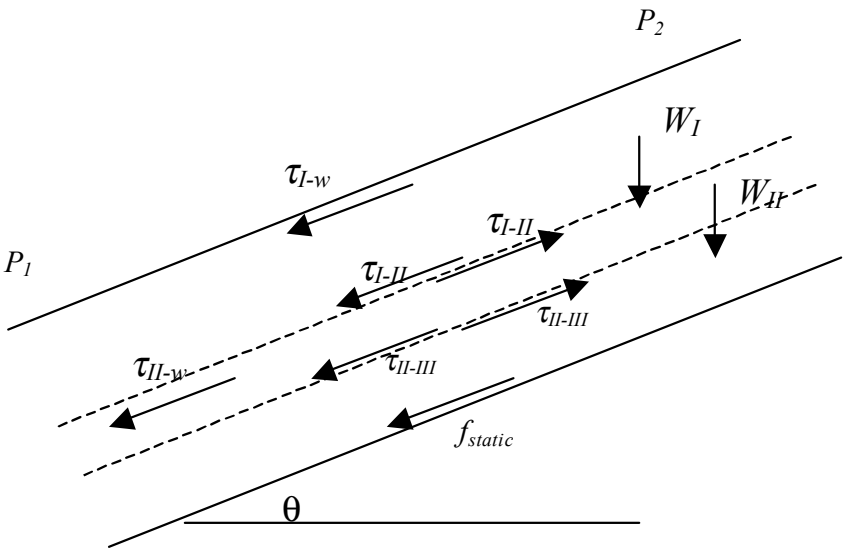

Fig. 4.1 – Layered wellbore representation

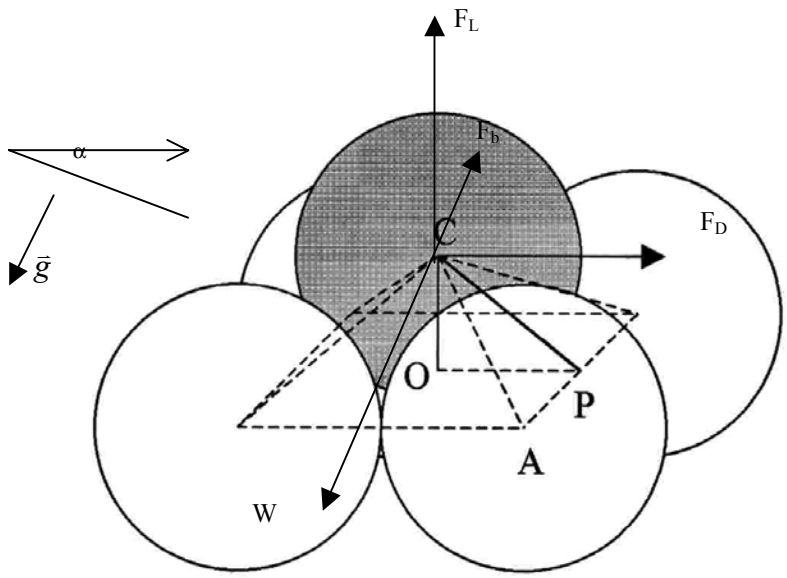

Fig. 4.2 – Representation of a cuttings particle resting on a cuttings bed

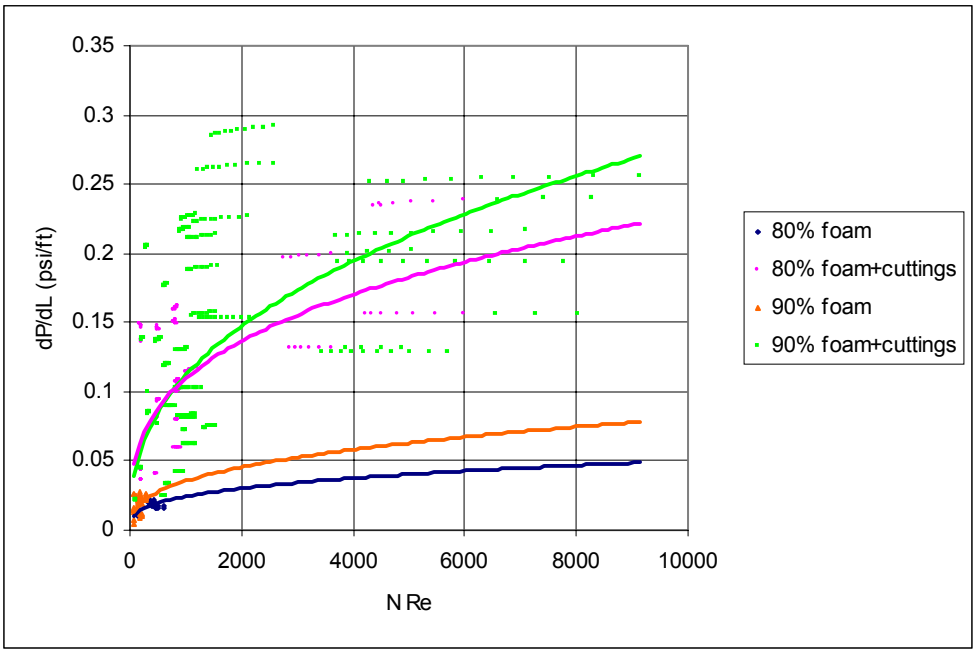

Fig. 4.3 – Comparison of pressure drop of foam with and without cuttings with varying Reynolds number

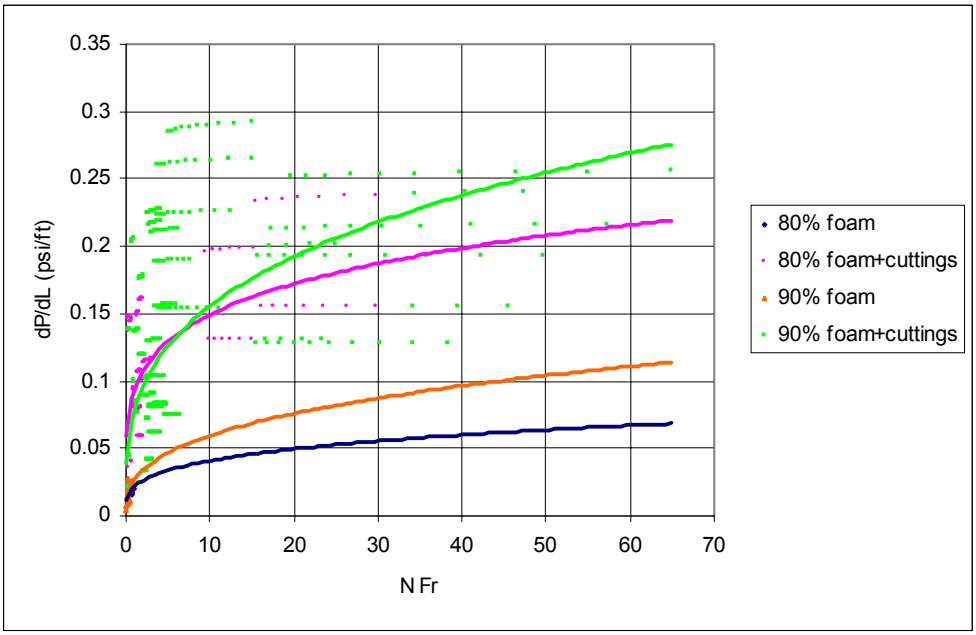

Fig. 4.4 – Comparison of pressure drop of foam with and without cuttings with varying Froude number

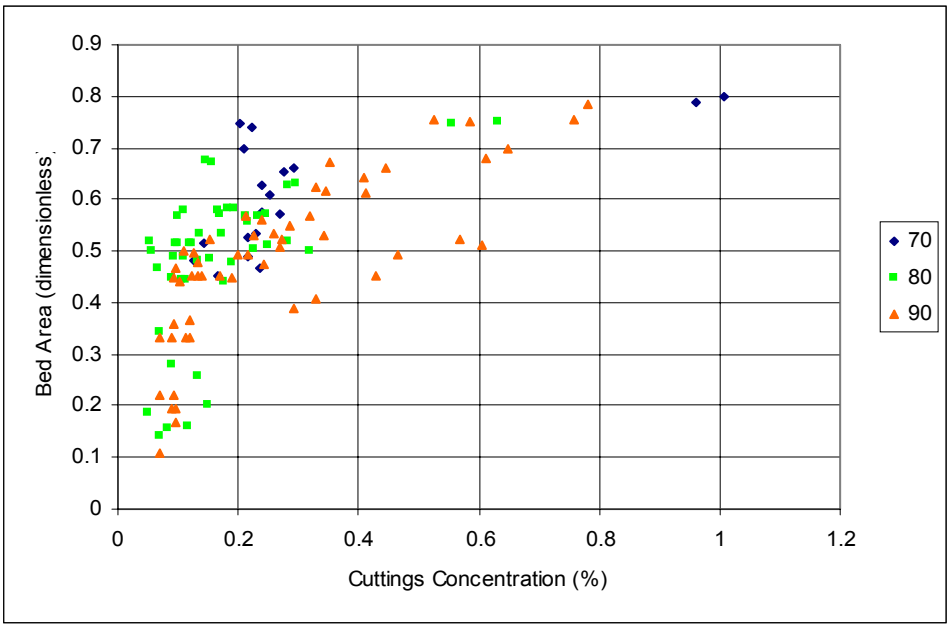

Fig. 4.5 – Effect of inclination on cuttings bed area. Cuttings concentration is the variable (foam)

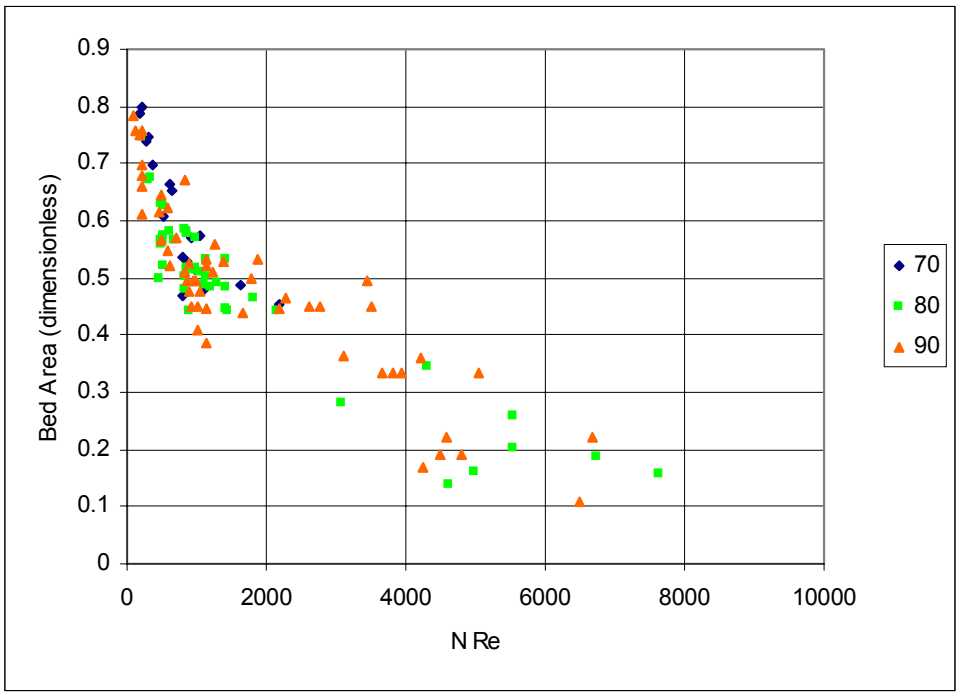

Fig. 4.6 – Effect of inclination on cuttings bed area. Reynolds number is the variable (foam)

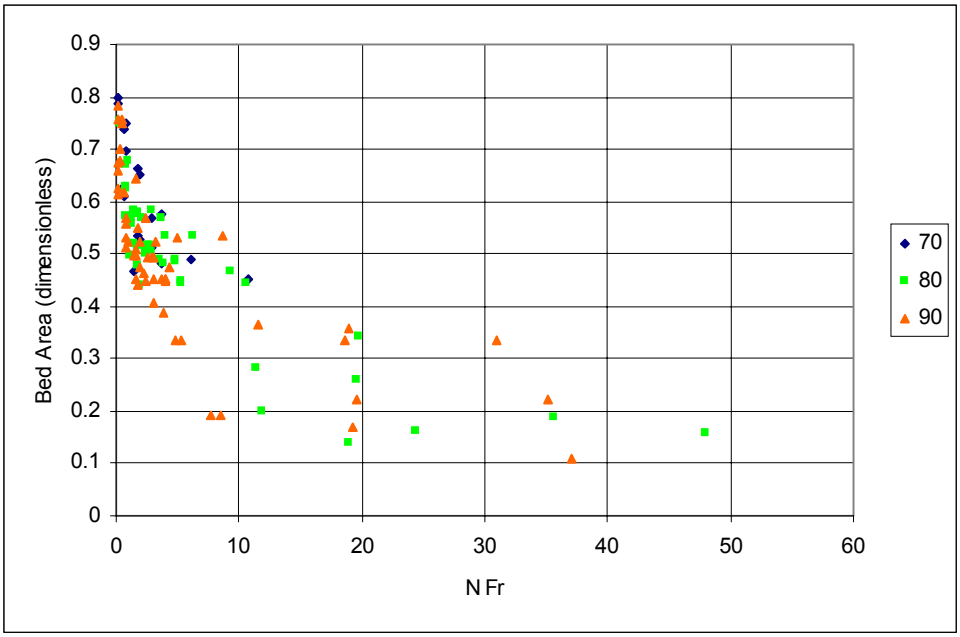

Fig. 4.7 – Effect of inclination on cuttings bed area. Froude number is the variable (foam)

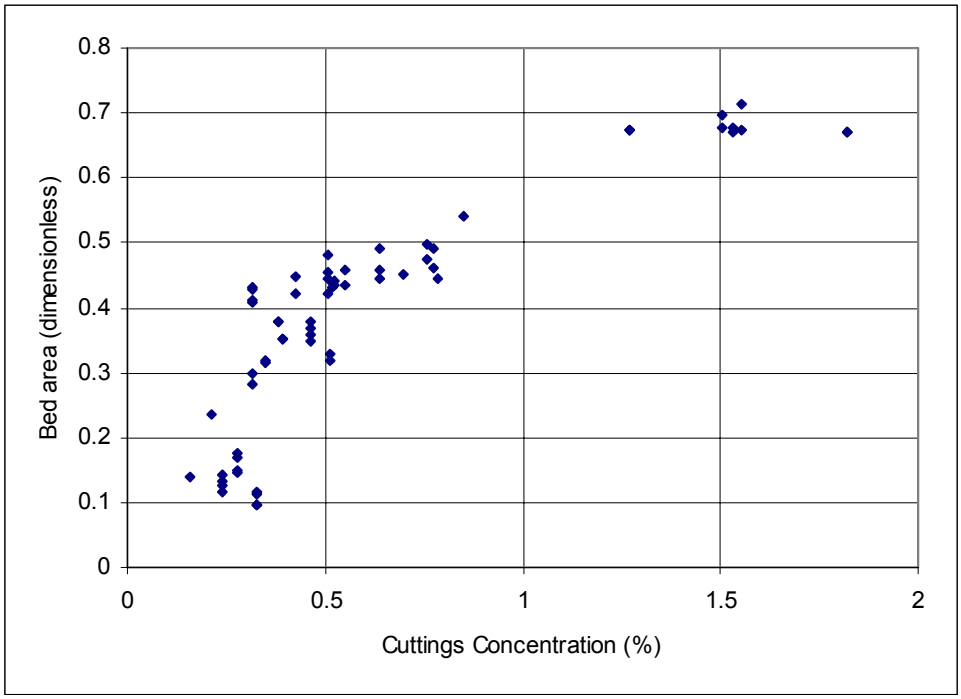

Fig.4.8 – Relation between the Cuttings Concentration and the Bed Area (water)

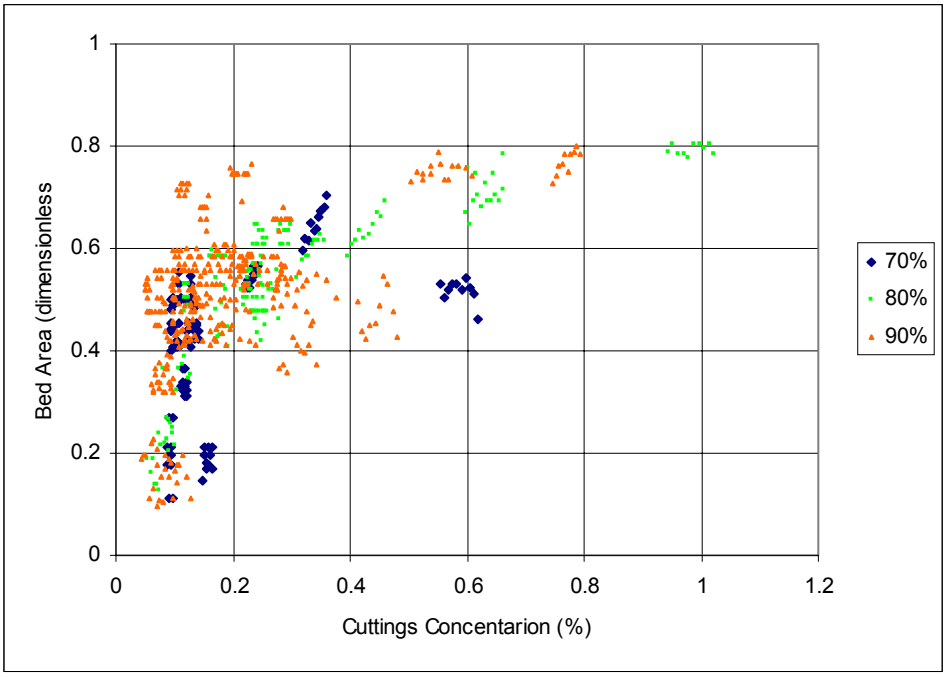

Fig. 4.9 – Relation between the Cuttings Concentration and the Bed Area (foam)

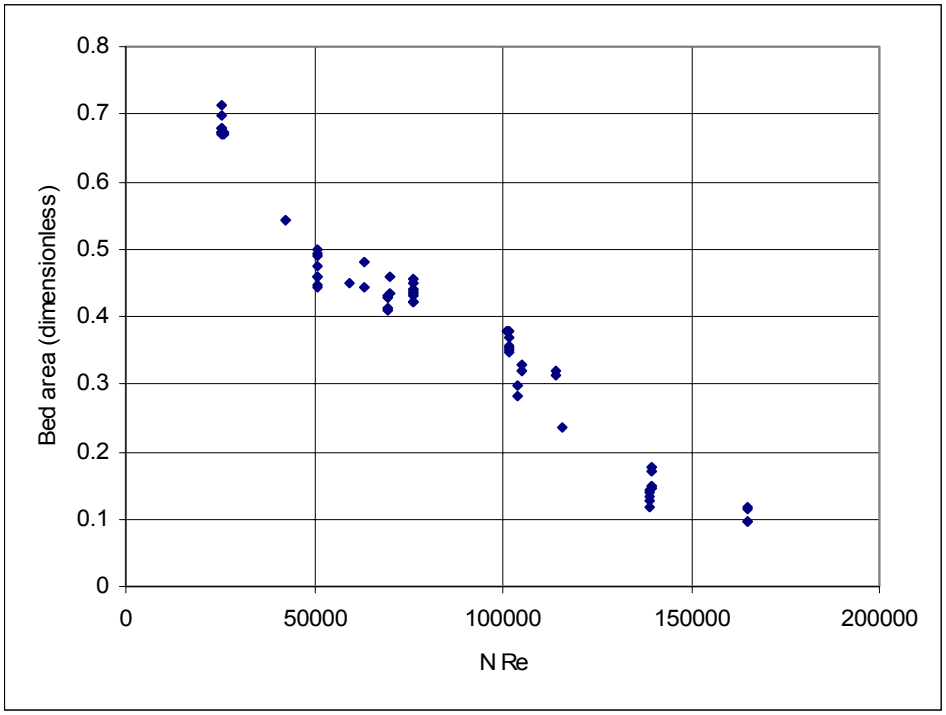

Fig. 4.10 – Relation between the Reynolds Number and the Bed Area (water)

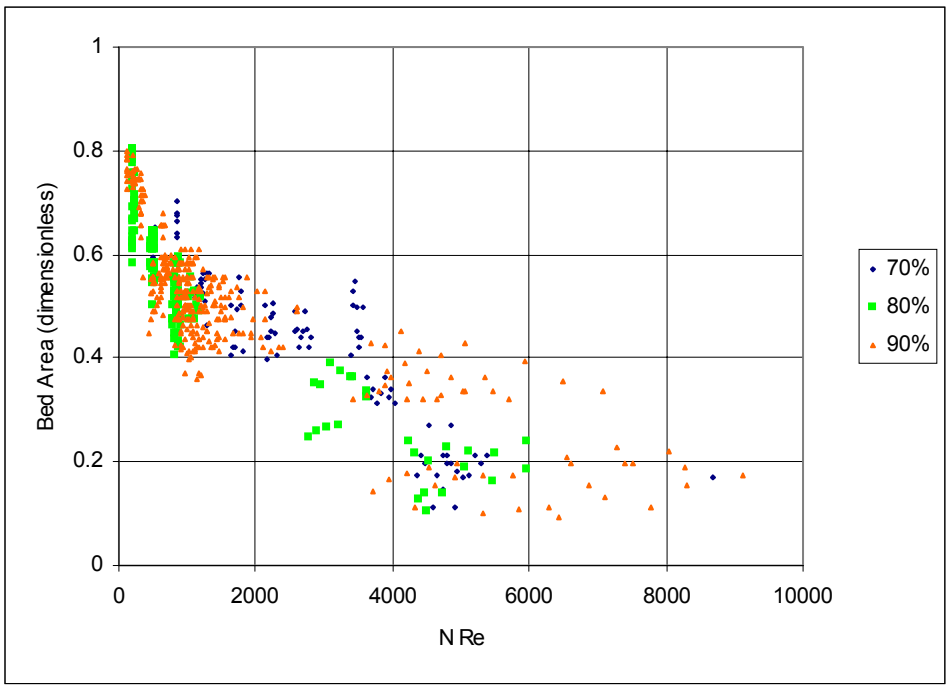

Fig. 4.11 – Relation between the Reynolds Number and the Bed Area (foam)

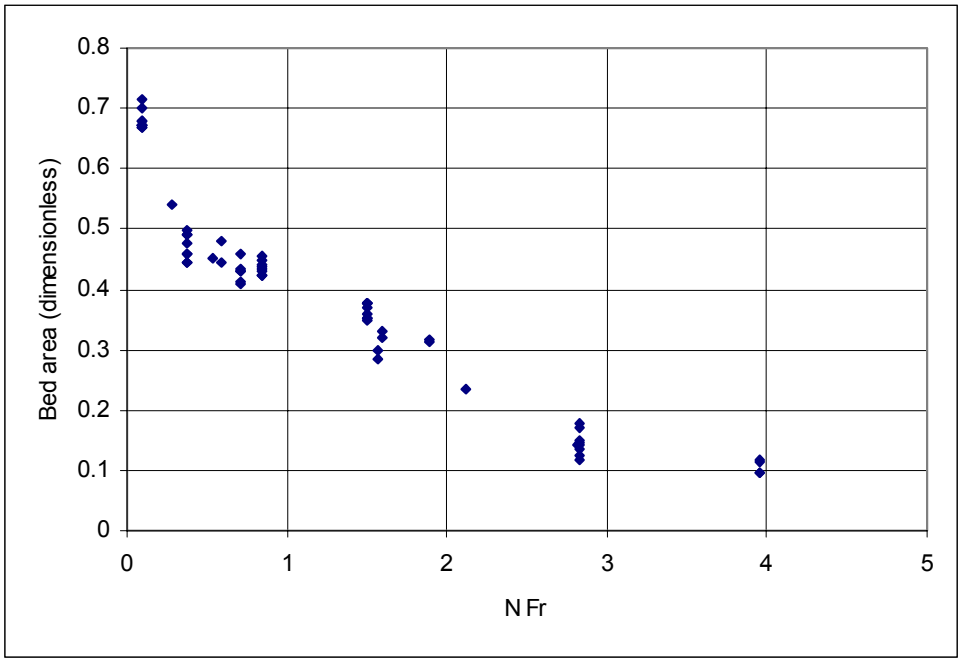

Fig. 4.12 – Relation between the Froude Number and the Bed Area (water)

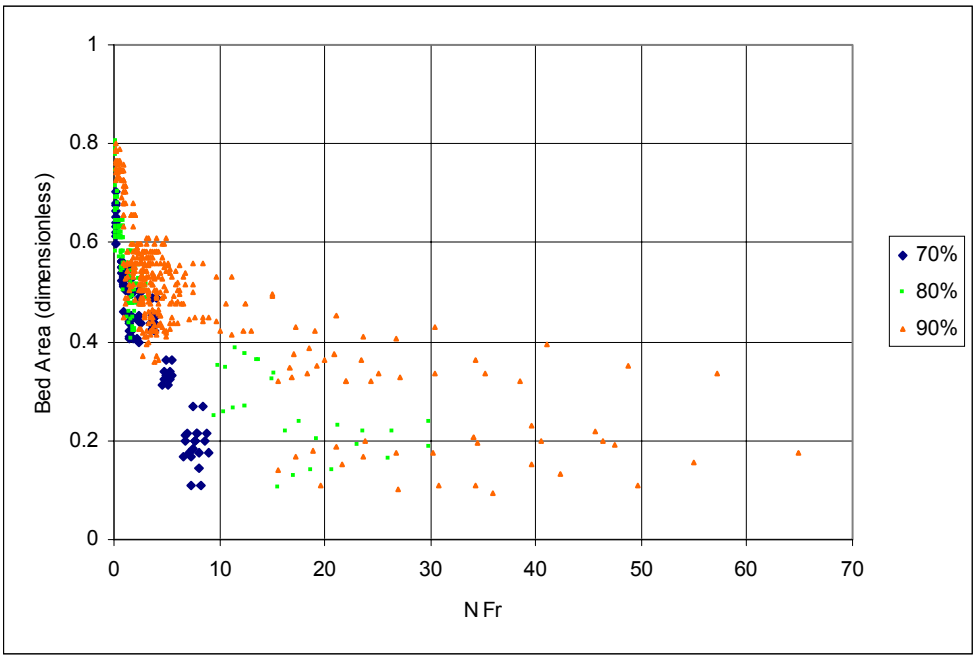

Fig. 4.13 – Relation between the Froude Number and the Bed Area (foam)

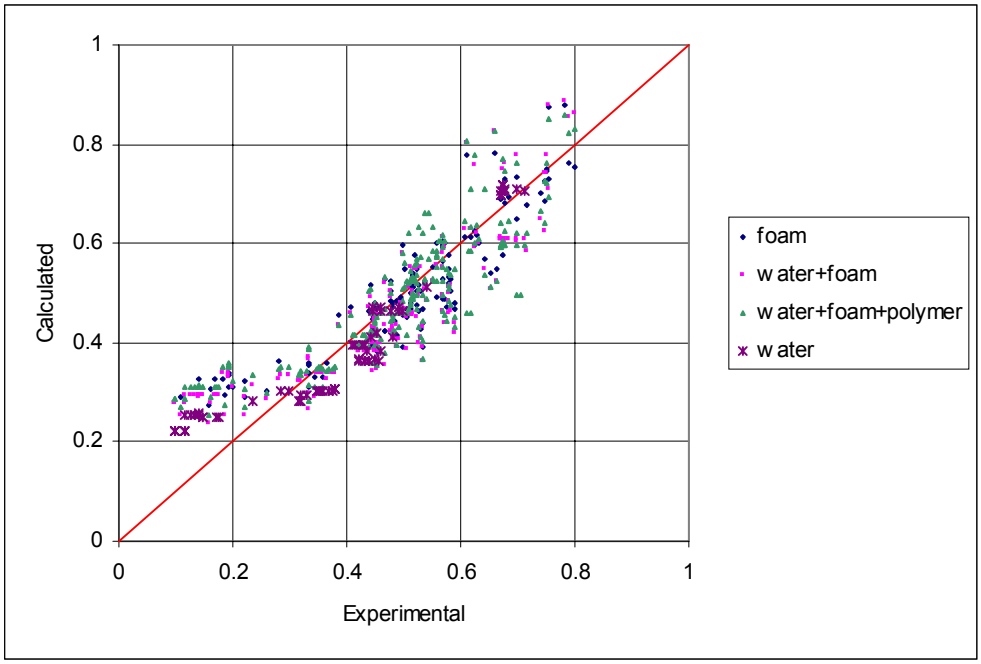

Fig. 4.14 – Comparison of Experimental Data and Calculated Values for Dimensionless Cuttings Bed Area

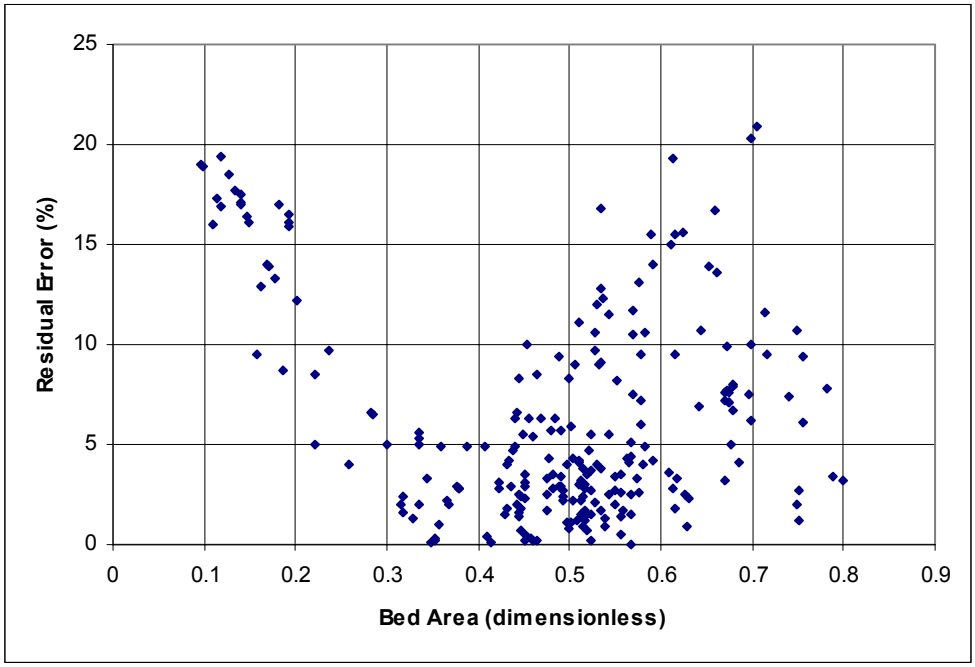

Fig. 4.15 – Error analysis of the model by comparisons with experimental data

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

Investigator: Affonso Marcelo Fernandes Lourenço (MS Candidate)

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 under a given gas-liquid ratio, temperature and pressure conditions.

ABSTRACT

The final configuration of the test matrix is reported below. Data analysis continues, and some results are reported and discussed. A new effect on rheological behavior of foams, related to the way foam is generated, was investigated. This effect encouraged the extension of the test matrix, and a new set of tests were performed. A preliminary discussion of the impact of the new foam generation on hydraulic behavior is presented in Section 5 of this report.

SUMMARY OF ACTIVITIES

The following major tasks have been undertaken since July 2001:

- Flow experiments with foam under elevated pressures and temperatures.
- Data analysis

Experiments

The most important achievement during this period was the completion of the test matrix. Table 5.1 shows the concluded test matrix.

Table 5.1 – Final Test Matrix

Pressure (psig)	**100**	**200**	**300**	**400**	**650**
Temperature (F)	**80**	**100**	**150**	**180**	
Qualities	**60**	**70**	**80**	**90**	
Flow rates	**3 different flow rates for each test**				
Pipe (in)	**2**	**3**	**4**		
Annulus (in)	**6 x 3,5**				

In addition, new experiments were conducted at similar conditions as shown in the previous matrix, but generating foam in a different way. Table 5.2 shows the experiments conducted with the new test procedure.

Table 5.2 – Extended Test Matrix

Pressure (psig)	**100**	**300**	**500**
Temperature (F)	**80**	**150**	
Qualities	**70**	**80**	**90**
Flow rates	**3 different flow rates for each test**		
Pipe (in)	**2**	**3**	**4**
Annulus (in)	**6 x 3,5**		

At this point it is important to clarify the meaning of the extended matrix and why it was proposed.

One of the difficulties encountered during the foam experiments was poor visualization of the flow. Since nor the view ports, that would be installed at the pipe sections, neither the online microscopy to characterize foam were available on time for the experiments, sample ports were installed at the 4 inch pipe.

These sample ports were nothing but high-pressure taps installed at the top and another one at the bottom of the 4 inch pipe. The top one was connected with a visualization cell allowing the sampling of foam under elevated pressure and temperatures. The top sample port was installed first and used since the beginning of the experiments. The intention was to use this sample port temporally until the installation of the view ports. After it was clear that the view ports would not be available on time for the experiments, the second sample port was installed at the bottom. The reason for installation was to verify the existence of a potential liquid layer flowing at the bottom of the pipes and annulus, and if it exists how severe would it be. The 4 inch pipe was chosen because the smallest velocities occur inside it and so it has the greater chance to present segregation. These sample ports plus the view port already installed at the upstream of the foam breaking tower, were the instruments used to visualize foam flow and design the best test conditions in terms of foam generation.

Although liquid was never observed at the sample port at the bottom, the observed foam was wet for the experiments at very low velocities. This was expected to occur once the foam generation is made upon a single pass through a static mixer. The flow of the mixture (air+water+surfactant) across the mixer at different velocities and different qualities generate different pressure drops, meaning different mixing energy and different foam texture. Considering that foam texture was considered a minor effect when compared to quality for example, this effect should not be a severe problem. The determination of limits of velocities at the mixer for proper foam generation under different test conditions was always made upon visualization of the flow at the view port and samples at the top sample ports. The results from the bottom sample port encouraged us to find a way to verify the true effect of the mixing energy on foam texture and rheology. Due to the reduced time to modify the design of foam generation, the usage of the ball valve installed upstream of the static mixer was proposed. More details about the new test procedure will be discussed in the following sections, but the results of increasing the shear rate and power while generating foam resulted in different texture foam with significant increase in the pressure drop measurements when compared to same test conditions and different foam generation. Then new tested were proposed and performed as shown in Table 5.2.

Modifications in Test Procedure

There were not drastic modifications in the test procedure. The only change was that after the stabilization of flow rates at the desired pressure, temperature and the start of surfactant injection, the ball valve was partially closed until a desired pressure drop across it was achieved. In reality, pressure drop was measured between the discharge of the Moyno pump and the pressure transducer installed in the 2 inch line.

Results and Comments

This section has the objective of show some results obtained from the experiments conducted in the ACTS flow loop. The data analysis is still in

progress and a final and detailed discussion about the results, as well as the reliability of the proposed hydraulic model, will be reported whenever it is completed. Therefore, this section will present some general trends about the effects of foam generation, quality, temperature, pressure and shear rate on foam rheological behavior.

Foam Generation and Quality

It was mentioned before that a change in foam generation procedure resulted in a different foam texture and consequently influenced in the rheological response of foams. Figure 5.2 shows the difference in the resultant shear stress for same test conditions, but different foam generation procedures.

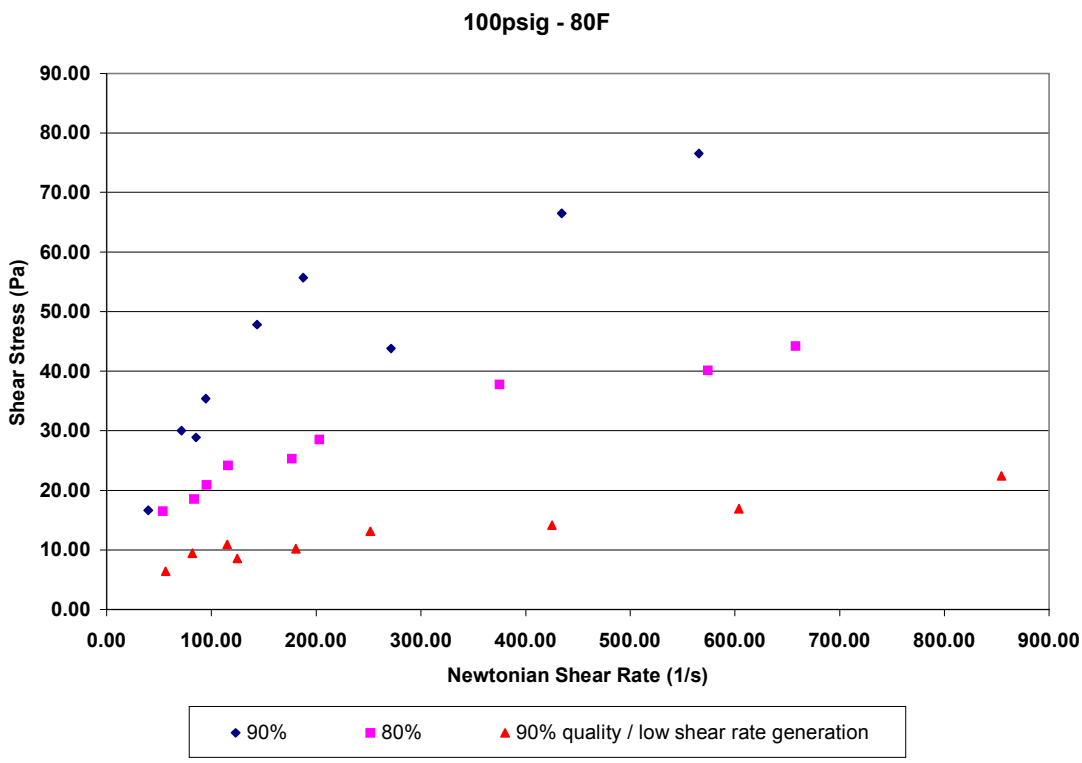

Figure 5.1 – Effects of Foam Generation

Figure 5.1 shows a drastic difference in shear stress for the same shear rate values for the flow of 90% foam at same temperature and pressure conditions, but generated with different shear rates. Basically the new foam generation procedure, by closing a valve upstream of the static mixer, created a higher shear rate and higher hydraulic power during the mixing of the air-surfactant solution mixture. The increase in shear rate and energy during foam generation produced stiffer foam with a smaller average bubble size distribution. The result was a considerably increase in pressure drop. What should be highlighted is that the effect of texture on rheology was more pronounced, according to these experiments, than expected and reported in the literature. Results indicated the existence of a range of shear rate and/or hydraulic power where good texture foam is achieved, but completed different rheological response can occur

depending upon the way foam is generated. After a certain level of shear rate there is no significant change in texture and any further increase in mixing power will not lead to changes in pressure drop. Therefore, the bubble size characterization linked with a hydraulic model becomes very important to accurately predict pressure drop under field conditions.

During the first phase of the new test set up, experiments were conducted to find a minimum pressure drop across the valve that would ensure, for all test conditions, that shear rate was above the mentioned range. The more adequate procedure would be control the hydraulic power, but it would require tremendous flexibility of the flow loop in terms of flow rates and pressure drop what is not available. Based on the flow loop capabilities the pressure drop was kept in 100 psid.

It is very difficult, most of time, to visually differ a satisfactory texture made at low shear from another at high shear. The attempt to characterize foam structure was a concern since the beginning of the project. Unfortunately, the ideal device to measure bubble size distribution and shape could not be finalized on time. In spite of this, an optional experimental set up to qualitatively compare the bubble size distribution of foams at different conditions was implemented. The micro scopy technique was used. Foams samples were collected under actual test conditions inside the viewing cell installed at the 4 inch pipe. Pressure could be preserved and temperature changes were considered negligible during sampling and testing time. The sample was transferred to the control room where a microscope was installed. Clearly the methodology presents disadvantages: static test, extra shear while collecting sample, drainage effect, bubbles deformation when in contact to glass. However, it may serve as a good comparative method of foam structure if these effects are minimized. The sampling was performed in the same way for all tests and with the smallest pressure drop between the pipe and the viewing cell as possible. The time frame for the entire operation of sampling and observation was less than a minute. The information is still under analysis, but the results confirmed a smaller bubble size distribution for the foam formed under high shear rates.

Figure 5.1 also brings information about quality effect and slip at wall. The 90% quality foam presents a higher effective viscosity than the 80% quality as expected. However, is important to mention that the graph presents Newtonian shear rate instead of the true shear rate at the wall. In addition, the slippage at the wall is not corrected. This disable the possibility of a more clear understanding of the quality effect once the shear rate at the wall is also a function of the general fluid behavior index, n'. Figure 5.2 shows the preliminary rheogram for the experiments at 400 psig and 180 F, and illustrates the previously commented effect.

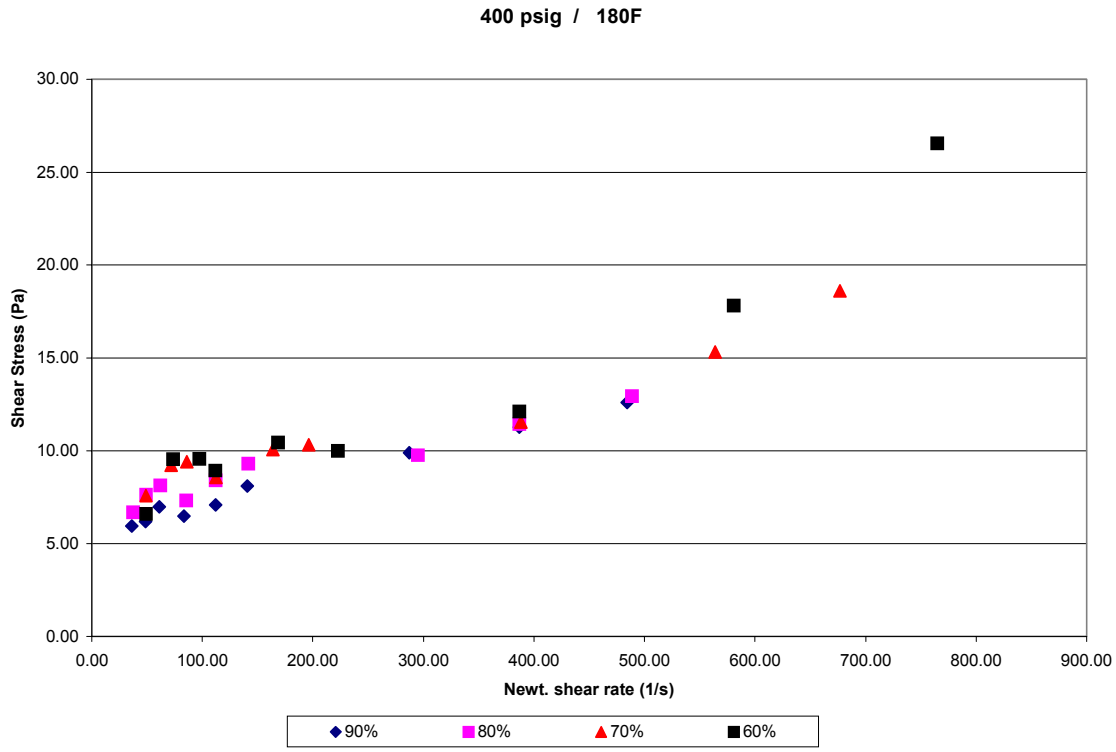

Figure 5.2 – Quality and Shear Rate Effects

It is not clear the effect of quality and apparently suggest similar effective viscosities for all range of qualities. The differences will be more pronounced after slip and shear rate correction.

Another interesting observation is the decrease of the slippage at the wall between the 3 and 4 inches pipes (points with low shear rates) for the foam generated at high shear rates.

Temperature Effects

Figure 5.3 shows the effect of temperature on the rheological behavior of foams based on the experimental data.

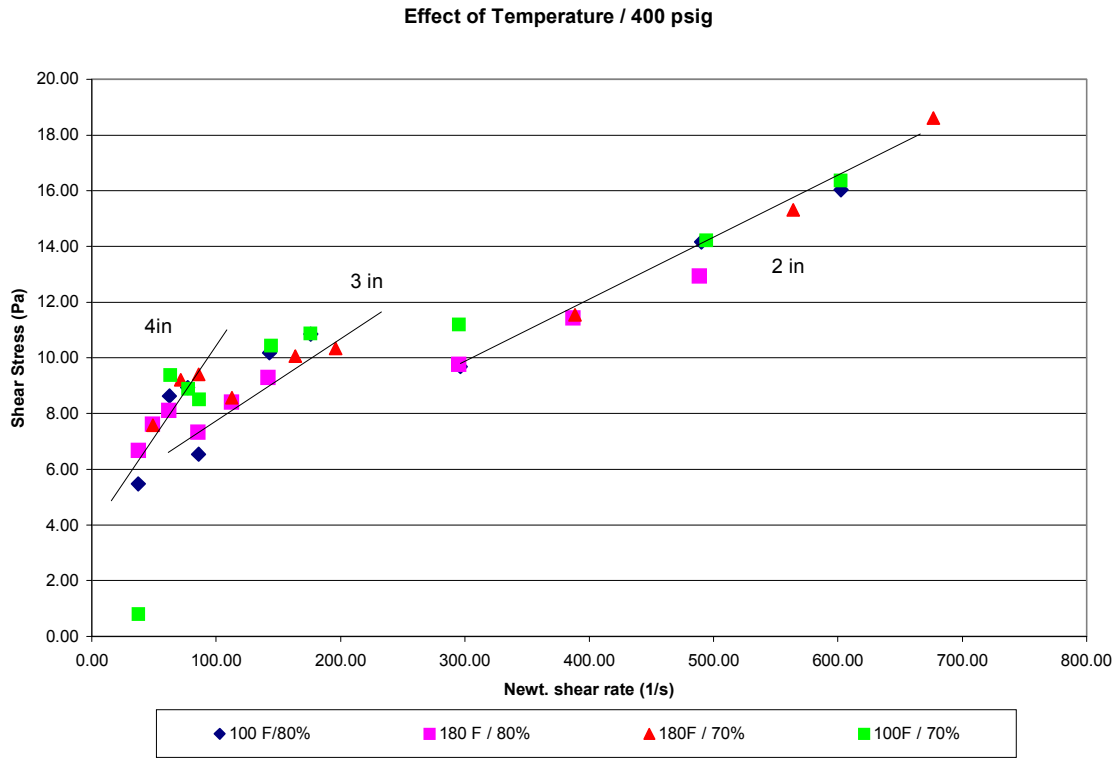

Figure 5.3 - Temperature Effects

Figure 5.3 does not indicate severe influence of temperature on the rheological response when comparing experiments at 100° F and 180° F in two different qualities. A thinning of foam is expected at higher temperatures and this trend is only slightly observed on Figure 5.3. Although no significant changes in the rheological response due to changing in temperature was found up to present time, difficulties were observed during foam generation at high temperatures. Foam with same quality and under same pressure required higher velocities at the mixer to be generated. The investigation of the different causes for the phenomena will be discussed in the final report.

Pressure Effects

Figure 5.4 shows shear stress versus shear rate for 90% quality foams at two different pressures.

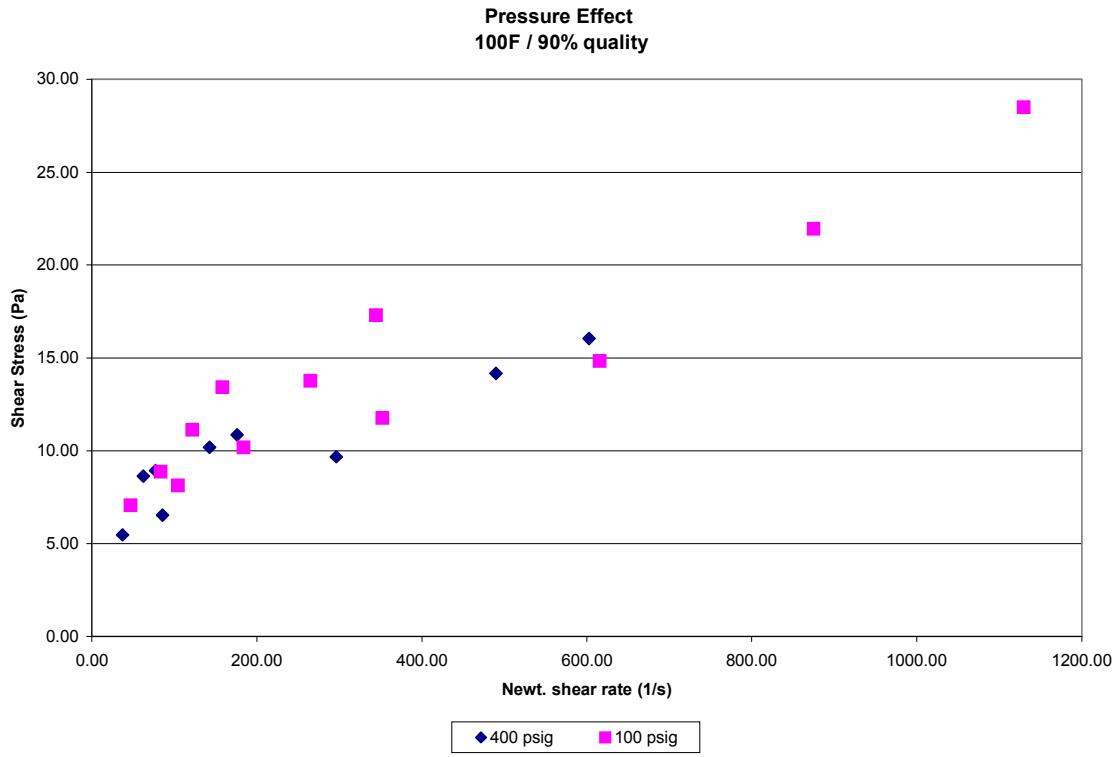

Figure 5.4 – Effects of Pressure

Analogously to the temperature effect, pressure does not seem to be a major effect on foam Rheology according to the results up to this point. The change in texture due to the foam generation under pressure does not influence significantly the foam effective viscosity under the simulated conditions.

Annular Flow and Additional Remarks

Figure 5.5 shows pressure drop profile with foam flow rate for two different qualities.

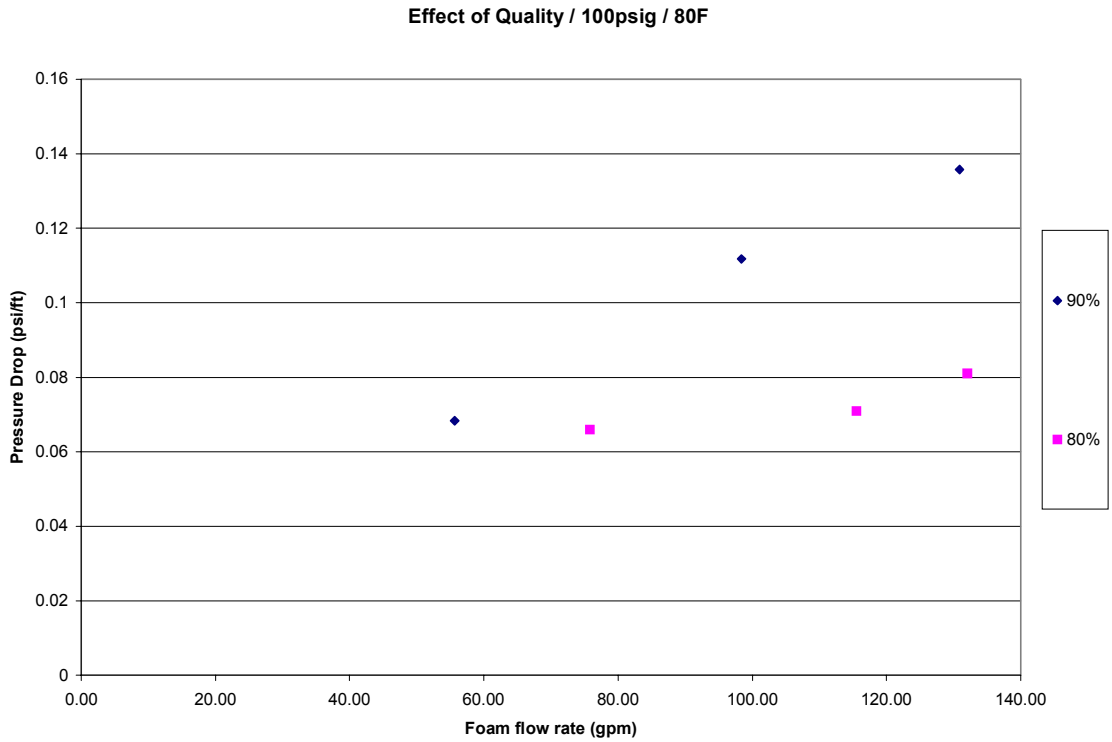

Figure 5.5 – Annular Flow of Foam

It is clear in the curve the higher effective viscosity of the 90% quality foam. The curve profile suggests the expected laminar flow with smooth increase of pressure drop with flow rate.

CONCLUSION

The conclusion of the experimental part of the project was accomplished. Data analysis will continue and reveal the reliability of the proposed methodology and hydraulic model to predict pressure losses during foam flow. The effect of foam generation on rheology was discussed and preliminary results reported. The effect of bubble size on foam rheology requires more attention in order to come up with a general hydraulic model to be used on the field.

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

Investigator: Lei Zhou (Ph.D. Candidate)

OBJECTIVES

1. Develop two phases flow model for aerated fluids under elevated pressure and temperature conditions inside an annuli in 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.

SUMMARY

Literature review on related knowledge and study the previous works done by TUDRP/ACTS are still continuing. Mathematical models are being development. Theoretical analysis of cuttings transport phenomena based on layered models is under development. Slug flow analysis is continuing. Measurements of Slug frequency, slug velocity and slug length by using nuclear densitometer is under investigation. Experiments are being planned to investigate the flow behavior of aerated mud under elevated pressure and temperature conditions. A test matrix has been designed.

PAST WORK

1. Literature review on cuttings transport and hole cleaning.
2. Literature review on drilling fluid Rheology.
3. Literature review on two-phase flow in pipe and annular.
4. Study of two-phase flow and slurry flow mechanism.
5. Temperature effect on drilling fluid Rheology and flow pattern have been studied
6. ACTS flow loop design review and A simulator was used to help sizing the pipe diameter. Analysis of particle transport mechanisms.
7. Analysis of particle transport mechanisms

PRESENT WORK

1. Modeling layered model considering air-liquid-cuttings three-phase flow under slug flow condition.
2. Set up test matrix for experiments.
3. Run experiments for two phases flow at elevated pressure and temperature conditions.
4. Developing computer simulator for prediction cuttings transport ability and two phases flow at EPET conditions.

FUTURE WORK

1. Literature survey on two-phase flow, drilling fluid Rheology and cuttings transport in pipes and annuli will continue.
2. Continue to model the layered-model of cuttings transport and modify existing models for two-phase flow-map prediction.
3. Continue to develop computer simulator for cuttings transport and two phase carrier fluid models.
4. Experiments will be planned to investigate the aerated-fluids flow behavior and cutting transport ability under elevated temperature and pressure conditions.

DELIVERABLES

1. Semi-annual Advisory Board Meeting (ABM) reports.
2. Two phases 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 the range of experimental conditions.

Test Matrix Set-up

In order to investigate two-phase flow at elevated pressure and temperature conditions, ACTS loop will be used to conduct experiments with air and water. The mixture will pass through a 2-in and a 3-in pipeline, an annular section (5.76" x 3.5"), and then a 4-in pipeline that connects to a combination gas separator and cuttings collection tank. A heater will heat the mixture up to 200 F^0 .

Different combinations of pressure, temperature, gas flow rate and liquid flow will be tested. For cuttings transport studies, the maximum liquid flow rate in the proposed test matrix is 260 gallon per minute. LabView software is used to supervise the whole system and all experiment data can be recorded. A computer program developed by Ashwin was used to predicted the pressure drop and flow pattern.

Table 6.1 - TEST MATRIX

SET 1					2"	2"	3"	3"
P(psi)	T(F)	Qg (GPM)	Ql (GPM)	Qg (SCFM)	Flow Pattern	Pressure Drop (Psi)	Flow Pattern	Pressure Drop (Psi)
100.00	80.00	114.19	80.00	100.00	SLUG	7.78	SLUG	0.99
100.00	80.00	114.19	100.00	100.00	DBUB	10.88	SLUG	1.37
100.00	80.00	114.19	120.00	100.00	DBUB	14.06	SLUG	1.80
100.00	80.00	114.19	140.00	100.00	DBUB	17.58	SLUG	2.28
100.00	80.00	114.19	160.00	100.00	DBUB	21.41	SLUG	2.81
100.00	80.00	114.19	180.00	100.00	DBUB	25.57	SLUG	3.39
100.00	80.00	114.19	200.00	100.00	DBUB	30.05	SLUG	4.03
100.00	80.00	114.19	220.00	100.00	DBUB	34.85	SLUG	4.73
100.00	80.00	114.19	240.00	100.00	DBUB	39.97	DBUB	5.73
100.00	80.00	114.19	260.00	100.00	DBUB	45.40	DBUB	6.51

SET 9					6" * 3.5"	6" * 3.5"	4"	4"
P(psi)	T(F^0)	Qg (GPM)	Ql (GPM)	Qg (SCFM)	Flow Pattern	Pressure Drop (Psi)	Flow Pattern	Pressure Drop (Psi)
600.00	140.00	16.92	200.00	80.00	SLUG	0.88	SLUG	0.87
600.00	140.00	21.15	200.00	100.00	SLUG	0.89	SLUG	0.88
600.00	140.00	25.37	200.00	120.00	SLUG	0.90	SLUG	0.89
600.00	140.00	29.60	200.00	140.00	SLUG	0.91	SLUG	0.90
600.00	140.00	33.83	200.00	160.00	SLUG	0.92	SLUG	0.91
600.00	140.00	38.06	200.00	180.00	SLUG	0.93	SLUG	0.93
600.00	140.00	42.29	200.00	200.00	SLUG	0.94	SLUG	0.94
600.00	140.00	46.52	200.00	220.00	SLUG	0.95	SLUG	0.95
600.00	140.00	50.75	200.00	240.00	SLUG	0.96	SLUG	0.96
600.00	140.00	54.98	200.00	260.00	SLUG	0.97	SLUG	0.97

Slug Frequency Prediction

Hill[1] and Wood identified seven variables that affect slug frequency most. Thus they indicate the need for five dimensionless groups. Although a large database was available to these authors, the wide range of parameters made their analysis difficult. Later they observed two parameters that appear to have a predominant influence on slug formation. One was the depth of stratified liquid film in the region of slug formation. The second parameter was the gas/liquid slip velocity. They expressed slug frequency as a function of these two parameters. By curve fitting horizontal slug frequency data, they derived the following correlation:

$$\frac{f_s d}{V_g - V_l} = 2.74 \frac{h_l}{1 - h_l}$$

Where h_l can be determined from the methodology proposed by Taitel and Dukler.

Tronconi[2] proposed a correlation between slug frequency and the properties of the waves that are responsible for slug generation. He observed that the characteristic frequencies of slugs during intermittent horizontal flow were related to the period of unstable waves responsible for generation of slugs in the inlet of the pipe. He studied the onset of slugging by estimating the wave properties in accordance with the theory of finite amplitude waves that was originally developed by Kordyban[3] etc. The resulting correlation was successfully tested with a limited amount of data from small diameter horizontal pipes.

$$f_s = 0.61 \frac{\rho_g V_g}{\rho_l (d - h_l)}$$

Taital[4] and Dukler developed a mechanical model for predicting slug frequency. Although their approach is consistent with many of the observed features of slug formation, solution of the partial differential equations are difficult to solve for the right solution.

Heywood[5] and Richardson used a gamma-ray technique to measure instantaneous values of the liquid holdup for air-water flow in a 1.65inch horizontal pipe. The measurement method enabled probability density functions and power spectral density functions of the holdup to be determined. From these functions, various slug characteristics including average slug frequency were estimated.

$$f_s = 0.0434 \left(\lambda \left(\frac{79.5276}{d} + \frac{V_m^{\,2}}{gd} \right) \right)^{1.02}$$

Zabaras[6] developed a model to predict the slug frequency for gas/liquid flows. He investigated Taital and Dukler's model in detail as an alternative unbiased prediction method. This model required the solution of the unsteady-state equations for mass and momentum by a finite difference technique. Total 399 data points were collected covering pipe diameter from 1 inch to 8 inch and inclined from 0 to 11° above the horizontal. He claimed that this model has 0% average error and 60% average absolute error, and his correlation represents a significant improvement in the slug frequency prediction accuracy over other existing methods.

Two nuclear densitometers have been calibrated and installed in the annular test section in order to measure the properties of slug flow and in-situ concentration of the multiphase mixture. The first densitometer was installed near the middle of the test section in order to avoid any inlet effects at the entrance to the annular test section. The second one was installed at 28-1/4 ft down stream of the first

one. The mixture density can be measured as a function of time, and an analysis of the acquired data can be used to calculate the slug length and slug velocity. Figure 6.1 shows the installation of the two nuclear densitometers.

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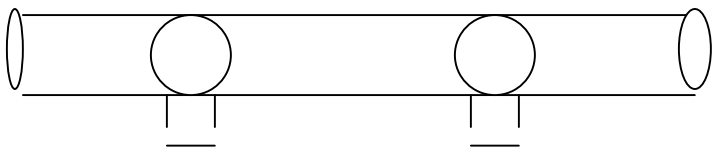

Figure 6.1 – Two Densitiometers on ACTS Flow Loop

When the front of a gas pocket passes the first densitometer, the indicated density will have a sharp drop because of the sudden increase in amount of gas phase present in the mixture flow. Then the front of gas pocket will reach the second densitometer to cause another density drop. Since the distance between the two densitometers is known and the time difference between the two density drops can be measured, the average velocity of the gas pocket can be computed.

Figure 6.2 shows the density profile versus time measured by the first densitometer, and Figure 6.3 shows the density profile versus time measured by the second densitometer. By comparisons of the recorded data, using the data acquisition system, the time at which the front of a gas pocket passes the first densitometer T_1 and the time T_2 when the front passes the second densitometer can be measured. Of course, the number of gas pockets that pass the densitometers in a certain time interval can be recorded.

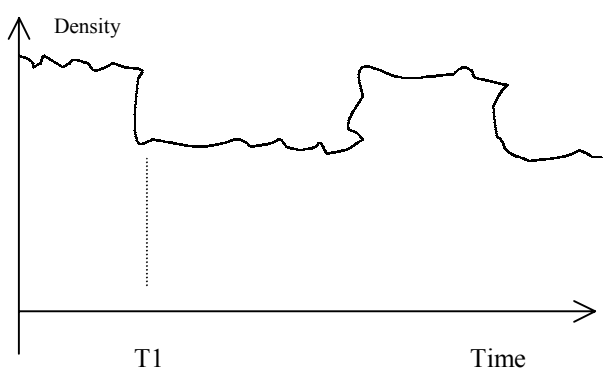

Figure 6.2 – Effects of Slugs on Density Profile at First Station

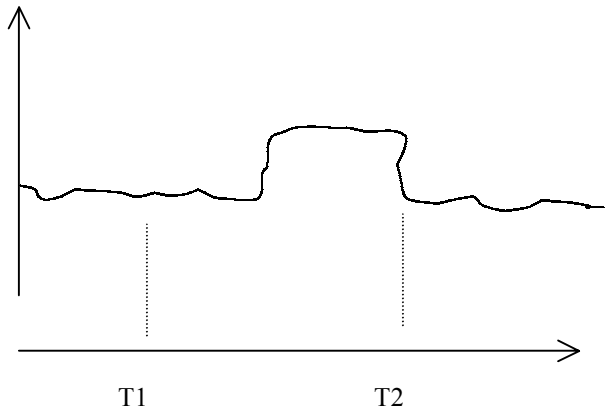

Figure 6.3 – Effects of Slugs on Density Profile at Second Station

Heywood and Richardson measured two-phase pressure gradients and time-average values of liquid holdup in a 42mm bore horizontal pipeline. The majority of the data correspond to the slug flow region, where rapid fluctuations in both wall pressure and holdup were observed. They recorded the instantaneous values of liquid holdup by rapid scanning of a vertical cross section of the pipe using the γ-ray absorption method, which enabled probability density function and power spectral densities of holdup to be determined.

If cross-sectional-area averaged holdup distribution along the pipe length is recorded by rapid scanning of the pipe at one point, a probability density function, P(α), can be estimated from holdup traces.

The PDF is defined by

$$P(\alpha_1) = \frac{dP(\alpha_1)}{d\alpha_1}$$

Where the quantity of P(α_1)dα_1 represents the probability that the holdup lies between the values α_1 and α_1+ dα_1. If a holdup trace has its holdup scale broken into equal increments of $\Delta\alpha_{1j}$, and the time scale broken into equal increments of Δt_j, then during the total time interval T, the holdup is seen to lie in the interval for a total n_i times,. This leads to the following equation.

$$\frac{n_i / N}{\Delta\alpha_{1j}} = \frac{1}{\Delta\alpha_{1j}} \sum_{j=1}^{n_i} \frac{\Delta t_j}{T}$$

Since the ratio $\sum \Delta t_j / T$ is the estimated probability that the holdup lies within the given interval $\Delta\alpha_{1j}$, it is seen that

$$\lim_{\Delta\alpha_{1j\to 0}} \left[\frac{1}{T\Delta\alpha_{1j}} \sum_{j=1}^{n_i} \Delta t_j \right] \to P_1(\alpha_1)$$

Where $P_1(\alpha_1)$ represents the PDF of the particular holdup trace examined and will have a particular form according to the nature of the flow passing through the gamma-ray beam during the sample time. If the sample time is large, then $P_1(\alpha_1)$ will approximate closely the true PDF, i.e.

$$\lim_{T \to \infty} [P_1(\alpha_1)] \to P(\alpha_1)$$

Alternatively, if several holdup traces (M) are obtained for constant flow condition, an average PDF may be defined by

$$\overline{P(\alpha_1)} = \frac{1}{M} \sum_{m=1}^{M} P_m(\alpha_1)$$

and

$$\lim_{M \to \infty} \overline{|P(\alpha_1)|} \to P(\alpha_1) \ .$$

The analysis of measurements with gamma-ray densitometers will continue when they are commissioned and fully operational as part of the data-acquisition system.

Nomenclature

V = velocity ft/s
P = probability density function of holdup
L = Length, ft
d = diameter, ft
f =slug frequency, sencond^{-1}
h = liquid holdup
Q = volumetric flow rate, ft^3/s
S = wetting perimeter, ft
T = time, second
g = gravity acceleration, ft/s^2

Greek Letters

ρ = density, lbm/ft^3
λ = dimensionless factor
α_1 = average liquid holdup

Subscripts

l = liquid film
g = gas phase
m = liquid –gas mixture
1 = gas pocket pass the first densitometer
2 = gas pocket pass the second densitometer

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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 drill pipe. 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/□-Ray and Optical. Of these, we will concentrate on Ultrasound as the primary approach for Task 11 and use X-Ray/□-Ray only if the first one is not successful

Team Composition:

The team for developing instrumentation to measure cuttings concentration and distribution (Task 11) charged with completing tasks 11 consisted of Dr. Gerald R. Kane and Dr. Kaveh Ashenayi both 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 CS. 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 data received.

Progress to Date

The PC board developed by our team has been assembled and has mostly been debugged. We have developed and finalized a set of commands and are in the process of finalizing the A/D portion. Also, we have tested the data averaging on board.

We had a problem with “NIMDA” virus but fortunately no data was lost. We have reinstalled and are progressing.

We will use software on the PC to collect data and analyze data. The data collection part has been completed and tested in conjunction with the printed circuit board. The software will start by allowing the user to setup the communication characteristics of the system. Then will proceed to identify the number of boards connected. This feature will allow us to expand (or reduce) the number of sensor rings without having to manually reconfigure anything in the software or hardware. The software will ask for a unique test number that will be used to identify the data collected in the database. This data will be time stamped and stored in an MS-Access database.

Also, we designed and built a clear plastic test cell. The objective is to use this test cell and visually verify the results obtained from the sensor boards. We have conducted very preliminary tests to check the echo problem.

Approach

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

The main approach to be investigated is the ultrasound transmission. 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 measure the sound received and compare it against sound transmitted. After suitable data processing we believe it will be possible to get an acceptable picture of what is inside the pipe. This is very similar to the MRI technique used by physicians.

Future Work:

We are to finish development of the firmware and test it. At the same time we are implementing our data analysis software.

In this stage we propose to use the clear plastic cell consisting of two rings of sensors with a concentric pipes about 4 feet long. Cuttings of known size will be placed in a predetermined location inside the cell (under a static environment). Using sensors we will try to locate these cuttings.

A PC based data acquisition system has been developed and will be tested. The software will be finished, and then it will be used to store and process information received from sensors.

The dynamic testing will be designed and implemented. Then the developed system will be used for modeling the cuttings behavior inside the dynamic cell. In this case, the fluid and cuttings will be moving but no drilling action will be simulated.

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 OBJECTIVES

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

Low quality, low pressure foam has been generated in the Dynamic Testing Facility. Both the frame grabber and video monitor captured bubble images. No bubble characterization was attempted at this time with our imaging software. We used both transmitted light and reflected light, however, residual cutting oil from the construction of the DTF coated the optical windows making transmitted light imaging particularly difficult.

8.3.2.2 Dynamic Testing Facility

Pressure testing the Dynamic Testing Facility (DTF) to 70 psi revealed that most of the 1-1/2" flanges leaked. After investigating this problem we found that all these flanges were incorrectly machined. The vendor replaced all at his cost although the main loop of the DTF had to be mostly disassembled to replace these flanges. Subsequent testing to 70psi revealed no leaking flanges. The bladder accumulator (Hydril) was installed this quarter and will be used to conduct the final pressure test to 150 psi.

The mixing system (air motor) and spray nozzle method of water addition function satisfactorily. The mixing rod would benefit from some additional method of support to prevent wobble.

All PVC fluid transfer systems seem to be functioning as designed. Figure 8.1 gives the latest schematic of the DTF, including the nitrogen manifold

8.4 PLANNED ACTIVITIES

8.4.2 Dynamic Bubble Characterization

- Complete leak testing of the DTF.
- Construct and install a clear section in the DTF's main loop.
- Install a Lexan protective shield around separator sight glass.
- Calibrate the nitrogen manifold needle valves.
- Purchase/install a chemical injection pump.
- Calibrate rates and volumes of the DTF
- Using the imaging instrumentation and software, develop a routine procedure for bubble analysis
- Adapt bubble characterization technology to the ACTF

8.4.3 Novel techniques for Bubble Characterization

- Continue development of foam quality method
- Continue development of technique for measuring average bubble size

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 Objective

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

The draft report of the Hazards Review has been completed and submitted to the Work Team for their comments and suggestions. After modifying the draft report to reflect the Work Teams input, the modified draft report will be given to the Review Team. Review Team, and Work Team members are given in Table 9.1

Table 9.1. Review Team and Work Team Members *

NAME*	REVIEW TEAM	WORK TEAM	AFFILIATION
Leonard Volk	X	X	Chairman (TU)
John Ford	X	X	Nat'l Petr. Tech. Office (US DOE)
Don Harris	X	X	Microelectronics Technician (TU)
Dave Hensley	X	X	Consultant (Tulsa Tech. Center)
Stefan Miska	X		ACTS Co-PI (TU)
Mark Pickell	X		ACTS Project Engineer (TU)
Troy Reed	X		ACTS PI (TU)
Jim Sorem	X		Sr. Assoc. Dean Engineering (TU)
Laurie St. Clair	X	X	Dir. Environmental, Health & Safety (TU)
Nicholas Takach	X		ACTS Co-PI (TU)
Mike Volk	X	X	Mgr. Research & Tech. Dev. (TU)

*Charles Alworth, a consultant with considerable background in piping design, electronic controls and law contributed significantly during our Hazards Review on April 30.

9.4 Planned Activities

- Incorporate suggestions from Work Team
- Present draft report to Review Team
- Incorporate revisions to draft Hazards Review report
- Develop an Action Plan based on recommendations in Hazards Review report
- Submit Hazards Review report and Action Plan to ACTF Advisory Board Members for their input.
- Modify Hazard Review report and Action Plan to incorporate input from Advisory Board Members for final report.
- Issue final Hazards Review report on ACTF.

10. TECHNOLOGY TRANSFER

Meetings with Petroleum and Service Companies

Conoco and Phillips are being invited to attend the November 13 ABM for the ACTS Project. The Conoco manager, that was interested in joining the project, was transferred before a Letter of Agreement was signed. We are still waiting to for his replacement to make a decision. We will continue to identify and contact additional oil and service companies that will benefit by participating in this project.

ACTS-JIP Advisory Board Meeting

The next Advisory Board Meeting will held on November 13, 2001. There are currently 10 members of the ACTS-JIP including, BP-Amoco, Chevron, Dowell Schlumberger, Halliburton, Intevep, JNOC, Petrobras, Statoil, Weatherford, and the U.S. DOE. Bachman has continued to provide a variety of surfactants, foam breakers and a corrosion inhibitor to the ACTS Project.