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ABSTRACT

This report includes a review of the progress made in ACTF Flow Loop development and research during 90 days pre-award period (May 15-July 14, 1999) and the following three months after the project approval date (July 15-October 15, 1999)

The report presents information on the following specific subjects;

- a-) Progress in Advanced Cuttings Transport Facility design and development,
- b-) Progress report on the research project “Study of Flow of Synthetic Drilling Fluids Under Elevated Pressure and Temperature Conditions”,
- c-) Progress report on the research project “ Study of Cuttings Transport with Foam Under LPAT Conditions (Joint Project with TUDRP)”,
- d-) Progress report on the research project “ Study of Cuttings Transport with Aerated Muds Under LPAT Conditions (Joint Project with TUDRP)”,
- e-) Progress report on the research project “ Study of Foam Flow Behavior Under EPET Conditions”,
- f-) Progress report on the instrumentation tasks (Tasks 11 and 12)
- g-) Activities towards technology transfer and developing contacts with oil and service company members.

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1. INTRODUCTION

The basic construction of the Advanced Cuttings Transport Facility (ACTF) was completed and the flow-loop was made operational in October, 1998 (Phase I). The 5-year plan for the Advanced Cuttings Transport Study has been approved by the U.S. D.O.E on July 14, 1999.

This report includes a review of the progress made in ACTF Flow Loop development and research during 90 days pre-award period (April 14-July 14, 1999) and the following three months after the project approval date (July 15-October 15, 1999)

2. EXECUTIVE SUMMARY

ACTS flow loop is currently operational with single phase flow under pressure. Calibration tests for differential pressure transducers and the mass flow meter have been completed. Temperature sensors have been installed and the calibration tests are being conducted. All the long lead material and equipment needed for the heating/ cooling system (Task 1- year 1) have been ordered and most of them already have been received.

Methodologies to be used for cuttings monitoring and foam bubble characterization have been identified. For cuttings monitoring, ultrasound transmission technique is going to be investigated. For bubble characterization, a technique of Microphotographic Analysis will be used. Experimental set-up for both cases are under development.

Experiments towards the better understanding of the flow behavior of synthetic drilling fluids under elevated pressure and temperature conditions will

start as soon as the heating/cooling system becomes functional. 50 bbls. of synthetic drilling fluids have been donated by the industry. HPHT testing of the synthetic drilling fluids using HPHT rotational viscometer have been conducted. A PVT apparatus available at the University of Tulsa, Petroleum Engineering department is being modified for PVT measurement of synthetic drilling fluids.

A new project on foam flow behavior under elevated pressure and temperature has been initiated. The project proposal is ready and will be discussed with the members of the ACTS-JIP at the upcoming November Advisory Board Meeting.

3. ACTF DESIGN AND CONSTRUCTION ACCOMPLISHMENTS

Progress in Advanced Cuttings Transport Facility design and construction since May 15, 1999 is presented in the following section.

a- Installed Pulsation Dampener

In order to absorb pulsation from the triplex Halliburton pump, a large Hydril pulsation dampener was installed on the pipeline near the discharge of the pump. This pulsation dampener consists of a flexible bladder contained within a steel shell. The space between the bladder and the steel shell is charged with nitrogen to a pressure of approximately 80% of the pipeline pressure. The differential provides a cushion, which absorbs the piston stroke pulses emitted by the pump. This has proved invaluable in removing excessive vibration from the loop piping. (see Figure-1)

b- Re-configured Rheology Piping for Series as well as Parallel Flow.

The initial design and construction of the test loop was such that the flow was either through the 2-inch rheology line or the 3-inch rheology line or both simultaneously. Initial experiments indicated that it would be very valuable to be able to confirm calculations knowing that the flow in both the 2-inch and 3-inch lines was exactly the same, e.g. series flow. Piping modifications were made which allow both parallel and series flow depending on which valves are open and which valves are closed. (see Figure-2)

c- Conducted Numerous Flow Tests to Establish hydraulic Base Line.

Significant progress has been made on instrumentation during this reporting period. After many repeated experiments this spring we isolated a problem with inconsistent data as being defective differential pressure transducers. Since identifying the problem, the manufacturer has worked closely with us on corrective measures and has replaced the instruments. A new differential pressure transducer which has a higher pressure drop capacity has been ordered, received, and installed on the 2-inch line. This now gives us the capability of using a 2, 3, and 4-inch pipe for rheology measurements.

In order to confirm that the instrumentation is working properly, a large number of flow tests at different operating pressures have been conducted. It is important that the results from these tests confirm standard calculations based on water before theoretical work can begin using non-Newtonian fluids. As a result of these tests we have been able to fine-tune the instrumentation to improve its accuracy and dependability.

d- Completed Preliminary Designs for Cuttings Injection Equipment.

In order to properly prepare budgets and scheduling for future years work, preliminary designs have been completed for the Cuttings Injection Equipment. (see Figure-3)

e- Completed Preliminary Designs for Cuttings Removal Equipment.

In order to properly prepare budgets and scheduling for future years work, preliminary designs have been completed for the Cuttings Removal Equipment. (see Figure-4)

f- Completed Preliminary Floor Layout Plans for Future Equipment.

All equipment planned for installation at any time during the 5-year construction schedule has been sized and located on a scale drawing. This will assure that the equipment is efficiently located for the operation of the test loop and that sufficient space has been allowed for the equipment to set and be operated and maintained. (see Figure-5)

g- Completed Designs for Second Mud Tank, Mud Mixing Equipment, and Mud Transfer Piping.

During meetings with the Advisory Board and others it was decided that, in order to utilize synthetic drilling mud as well as other fluids in the testing program, it would be very advantageous to have a second mud storage tank, the ability to mix different fluids, and be able to transfer fluids from one tank to another. Designs have been completed to do that. (see Figure-6)

A 100 Bbl. mud storage tank and a 5 Bbl. mud mixing tank have been ordered and received. They and their connecting piping will be installed at the time the heating and cooling units, heat exchangers, and their connecting piping are installed. Tank and piping insulation will follow immediately after that. The addition of these new tanks will allow us immediate on site access to two different test fluids, the ability to mix test fluids in useful quantities, and the ability to transfer test fluid from one tank to the other.

h- Revised the Process and Instrumentation Diagram.

Due to the extent of process, instrumentation, and piping changes that have occurred since November, 1998, the Process and Instrumentation Diagram has been revised. (see Figure-7)

i- Researched Literature on Foam Breaking Techniques.

Foam drilling technology is not new however the most common technique, by far, for land based operations is to allow the used foam to degrade in an open pit. Because of cost, space, and environmental limitations, offshore operations have used various physical and chemical methods to break the foam. Similar limitations exist on the ACTF loop. Since November, 1998, an extensive literature review has been undertaken to understand what has been done at other locations.

j- Conducted Numerous Laboratory experiments on Foam Breaking.

Based on the literature review and discussions with vendors and other researchers, several techniques and combinations of techniques involving surface spray, centrifugal separation, chemical foam breaker, different injection methods, and different foam qualities and quantities have been tried. As a result of this work, a water surface spray has been chosen for the initial

experimentation studies on the Low Pressure Loop. Work will continue to refine the techniques for the High Pressure Loop.

k- Conducted Numerous Laboratory experiments on Foam Making.

In order to finalize the proper combination of air, surfactant, water, and agitation needed to produce the quality and quantity of foam we want, several experiments were conducted, revised, and perfected.

l- Completed Detailed Quotations on Heating and Cooling Equipment.

In anticipation of placing an order for the Heating and Cooling equipment as soon as possible after award of the 1999 grant, the apparent low bidder for the equipment has submitted responses to several detailed questions regarding warranty, mechanical operation, and performance characteristics of their offering. All vendors responding to our Request for Quotation completed a detailed analysis of their equipment's performance when operating at a specific list of parameters.

Heating and cooling equipment has all been placed on order and many parts have already been received. The heater is an indirect natural gas fired boiler manufactured by Heatec, Inc. It has a capacity of 2.0 million BTUs/hr. Heat transfer will be thru an Alfa Laval, Inc. plate exchanger. The transfer fluid will be circulated from the heater skid provided by Heatec. Controls will be possible both locally on the heater skid and by the computer located in the control room. Cooling will be done thru a Baltimore Aircoil Company evaporative condenser which will allow the test fluid to be taken down to near wet-bulb temperature. The transfer fluid will be circulated by a small transfer pump thru another Alfa Laval, Inc. plate exchanger. The cooling tower has a capacity of 1.5 million BTUs/hr.

As a result of this new equipment we will be able to increase the temperature of the test fluid from (as an example) 70 degrees F to 130 degrees F in approximately 1 hour. To return the test fluid to 70 degrees F from 130 degrees F, in order to repeat the experiment, it will take approximately 1 1/2 hours. Our maximum temperature will be 200 degrees F.

m- Completed Designs for 1999 Piping Modifications.

Detailed designs for the piping modifications planned for the 1999 –2000 construction season have been prepared. (see Figure-8)

Issued	Drawn	WSP	Approved

No.	Revision / Activity	Date
0		

Pulsation Damper	Rev 0
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No.	Revision / Activity	Date
0	Released for May, 99 ABM	4/15/99

THE UNIVERSITY OF TULSA	ACTF Advanced Curing Technology Facility
Issued	Drawn
Approved	Checked
1999	1999
Revised	Revised
0	0

No.	Revision / Activity	Date

Issued	MP
Drawn	MP
Approved	SPH

ACTF

Year 5 Plan View

Rev 0

No.	Revision / Activity	Date
			<div> <div>Issued</div> <div>Drawn</div> <div>Approved</div> </div> <div> <div>MJP</div> <div>SZN</div> </div>
			<div>'99 Piping Modifications</div> <div>Rev 0</div>	

4. STUDY OF FLOW OF SYNTHETIC DRILLING FLUIDS UNDER ELEVATED PRESSURE AND TEMPERATURE CONDITIONS

This study has been initiated in September 1998. The project proposal has been prepared and presented at the November 1998 Advisory Board Meeting of ACTF-JIP. The proposal was well received by ACTF and TUDRP member companies. A project progress report was presented at the May 1998 Advisory Board Meeting of ACTF-JIP. The following section presents the progress made in this project since November 1998.

Project Title : **Study of Flow of Synthetic Based Drilling Fluids Under Elevated Pressure and Temperature (EPET) Conditions**

Investigator : Barkim DEMIRDAL

Objectives:

1. To investigate the rheological behavior of synthetic based drilling fluids by using Advanced Cutting Transport Facility (ACTF) as a pipe viscometer under elevated pressure and temperature (EPET) conditions
2. To verify available empirical and semi-empirical turbulent flow models for estimating turbulent pressure losses by using experimental data
3. To develop a computer program that predicts parasitic pressure losses for various flow rates, composition of mud and wellbore geometry during the flow of synthetic based drilling fluid

4.1 INTRODUCTION

Oil based drilling fluids are preferable for better shale inhibition, wellbore stabilization and lubrication when compared with water based drilling fluids. However, starting in the 1980's, it was understood that oil based drilling fluids, even the low toxicity mineral oils, did not biodegrade adequately in a cuttings pile to allow degradation of oil and recovery of the seabed within an acceptable period of time. Increasing legislative restrictions on the discharge of cuttings contaminated with mineral oil resulted in the development of new drilling fluids that are more acceptable to the environment and able to achieve the properties of oil base muds. In addition to being environmentally safe, synthetic based drilling fluids also avoid some disadvantages encountered in deep and ultra-deep wells drilled with water base muds. These include, gas hydrate formation in blow-out preventers and hole cleaning problems in large diameter riser sections. In addition to reducing these effects, lessen solubility of gas in synthetic based drilling fluids allows quicker detection of gas influx to the system so that a well can be controlled more easily.

Hydraulic design calculations and optimization programs based on these hydraulic calculations have vital importance for achieving either high ROP and/or low cost. Parasitic (frictional) pressure losses is one of the key parameters to determine ECD (Equivalent Circulating Densities) and pump pressures, which in

turn affects surge/swab pressures while tripping, sizing of mud pumps, well control and general well planning. Parasitic pressure losses can be obtained either by using electronic devices and measuring the actual pressure of the system while drilling (Pressure While Drilling (PWD) and Measurement While Drilling (MWD) tools) or by using pressure loss equations derived for flow of non-Newtonian fluid flow in pipes and annuli.

The successful prediction of frictional pressure losses by using these equations depends on the accurate representation of the drilling fluid rheology. Usually, rheology of the fluid is determined under ambient conditions and extrapolated to downhole conditions. However, it is known that rheology of drilling fluids is influenced by many parameters (temperature, pressure, shear history, composition of the drilling fluid) and show different properties under high or low shear rates. Since synthetic based drilling fluids are more sensitive to temperature and pressure than any other type of drilling fluid; a detailed study of their high pressure and high temperature behavior is needed to understand how differences in rheological characteristics might affect hydraulics. This part of the research will be conducted both by using an HPHT rotational viscometer and a pipeline viscometer section of the Advanced Cutting Transport Facility (ACTF). The effect of cyclical variations in temperature and pressure on the fluid's rheology can be observed by comparing closed pipe-loop viscometer data with HPHT rotational viscometer data.

After determining the rheological model of the synthetic fluids under high pressure and temperature, the experimental frictional losses will be compared with theoretical pressure losses derived by previous investigators to see whether these equations can be used to determine pressure losses efficiently. Friction factor vs. Reynolds Number charts will be obtained for the particular mud system under investigation and the effect of drag reducers on pressure losses will be determined. In this way, applicability of laminar flow based semi-empirical or empirical pressure loss equations for turbulent flow conditions will be determined and necessary changes will be made to obtain more accurate predictions.

To do this analysis, the ACTF Loop will be used as a pipe viscometer. It has a wide range of pressure and temperature with upper limits of 1400 psig and 200 °F. The flow rate can be increased up to 300 gpm, which allows high shear rates comparable to those encountered in a drill pipe during drilling operations. Fann Model 70 Viscometer will also be used as HPHT rotational viscometer to determine HPHT rheological properties of the mud under investigation.

4.2 SCOPE OF THE PROJECT

Experimental analysis of synthetic based drilling fluids under elevated pressures and elevated temperatures will be carried both by using an HPHT rotational viscometer and the ACTF Loop located on the North Campus of The University of Tulsa. Rheological characterization of the fluids obtained by rotational viscometer and pipe viscometer will be compared. Pressure losses obtained by the experiments will be compared with empirical and semi-empirical equations to examine the applicability of laminar flow theory for turbulent flow. The Friction factor (f) vs. Reynolds number for a given fluid will be plotted. The

effect of drag reducers on the pressure losses and rheology of the synthetic drilling fluid will be analyzed. A computational tool that calculates frictional pressure losses and equivalent circulating density for a given fluid system will be developed.

4.3 THEORY OF TURBULENT FLOW OF NON-NEWTONIAN FLUIDS:

4.3.1 Turbulent Flow of Non-Newtonian Fluids in Pipes

The behavior of a flowing fluid is determined by the flow regime, which in turn has a direct effect on the ability of that fluid to perform its basic functions. Flows are generally defined as either laminar or turbulent. Between them, there is a transition region, where a fluid has both laminar and turbulent characteristics. This region is controlled by the relative importance of viscous forces and inertial forces in the flow. *Laminar flow* is flow in which fluid layers moves parallel to the walls of the flow channel and each other in smooth lines. This type of flow can be represented by the Navier-Stokes equations. On the other hand, flow that does not satisfy the Navier-Stokes equations for a viscous fluid that flows with relatively high Reynolds numbers are often termed *turbulent flow*. In turbulent flow both the velocities and pressure gradients are fluctuating and these fluctuations are random. To define mean velocity, temperature distributions and pressure losses in turbulent systems, either semi-empirical and empirical theories or application of statistical mechanics should be used. The latter is beyond the aim of this research, so this study will deal with semi-empirical and empirical theories that are developed to define turbulent flow systems.

Early investigators made several attempts to define turbulent flow of non-Newtonian fluids. They assumed that, the non-Newtonian fluid in laminar flow as effectively Newtonian in turbulent flow, any variation in apparent viscosity under turbulent conditions being disregarded. Thus non-Newtonian friction data for tubes were correlated on the conventional friction factor-Reynolds Number curve for turbulent Newtonian fluids, using variety of terms for viscosity in the Reynolds number.

Caldwell and Babbitt [1] proposed that apparent viscosity of Bingham-Plastic fluids is the viscosity of the dispersion medium, which is water in the case of water base drilling fluids.

Hedstrom and Weltmann [2] introduce the concept of plastic viscosity (η) to use in the N_{Re} equation for Bingham-Plastic fluids.

For power-law fluids in turbulent flow, Weltmann [3] proposed an apparent viscosity at the pipe wall, $\mu_a = g_c \tau_w / (-du/dr)$, and that N_{Re} is a function of fluid behavior index, n .

Alves, Boucher and Pigford [4] introduced a turbulent viscosity that can be obtained by using f vs. N_{Re} curves that were sketched for Newtonian fluids.

Extensive theoretical and experimental studies on turbulent flow of non-Newtonian fluids were carried by Metzner and Reed [5], and Dodge and Metzner [6]. It is known from power-law fluids that the relation between wall shear stress, $\tau_{r=R}$, and wall shear rate, $8V/D$, at laminar flow can be given as;

$$(\tau_{rx})_{r=R} = \tau_w = K' \left(\frac{8V}{D} \right)^{n'} \dots\dots\dots(1)$$

The Fanning Friction factor is defined as;

$$f = \frac{g_c \left(\frac{D \Delta P}{4L} \right)}{\frac{\rho V^2}{2}} = \frac{g_c \tau_w}{\frac{\rho V^2}{2}} \dots \dots \dots (2)$$

Substituting Equation (1) into Equation (2);

$$f = \frac{2g_c}{\rho V^2} K' \left(\frac{8V}{D} \right)^{n'} = \frac{16\gamma}{D^{n'} V^{2-n'} \rho} \dots \dots \dots (3)$$

For the case of laminar, Newtonian flow
;

$$f = \frac{16\mu}{DV\rho} = \frac{16}{N_{Re}} \dots \dots \dots (4)$$

At this point they assume that the Power-Law Reynolds number can be derived from Newtonian fluid by equating (3) and (4) as follows:

$$N_{Re} = \frac{D^{n'} V^{2-n'} \rho}{\gamma} \dots \dots \dots (5)$$

The above derivation shows that all fluids, which are not time dependent, must obey conventional Newtonian friction factor vs. Reynolds Number when flow is laminar. As a next step, they predicted the velocity elements of flow in turbulent, laminar and buffer zones. For fully-turbulent flow of a non-Newtonian fluid in a smooth tube, local velocity in the direction of flow is a function of;

$$u = f(R, \rho, \tau_w, g_c, K, n, y) \dots \dots \dots (6)$$

For the flow within the wall region, velocity is independent of the radius of the pipe in the laminar boundary layer, the transition zone and the outermost turbulent core, so that;

$$u = f(\rho, \tau_w, g_c, K, n, y) \dots \dots \dots (7)$$

For the velocity defect, which is the difference between the maximum local velocity in the center of the pipe (u_m) and local velocity (u), it can be stated that the effect of viscosity is negligible in turbulent fluctuations that occur in the core. For non-Newtonian fluids, velocity defect ($u_m - u$) is independent of K but dependent on n .

$$u_m - u = f(\tau_w, g_c, \rho, R, y, n) \dots \dots \dots (8)$$

Above three relations are solved by using the Buckingham's Pi Theorem;
A general function for u/u^* at any radial location,

$$\frac{u}{u^*} = f_1(Z, \xi, n) \dots\dots\dots(9)$$

where

$$Z = \frac{R^n \rho (u^*)^{2-n}}{K} \dots\dots\dots(10)$$

$$u^* = \sqrt{\frac{\tau_w g_c}{\rho}} \dots\dots\dots(11)$$

$$\xi = \frac{y}{R} \dots\dots\dots(12)$$

A general function for u/u^* within the wall region,

$$\frac{u}{u^*} = f_2(Z \xi^n, n) \dots\dots\dots(13)$$

A general function for $(u_m - u)/u^*$ in the turbulent core,

$$\frac{u_m - u}{u^*} = f_3(\xi, n) \dots\dots\dots(14)$$

A general function for $(u_m - V)/u^*$,

$$\frac{u_m - V}{u^*} = P_n \dots\dots\dots(15)$$

Assuming that transition and laminar layers are thin for Newtonian fluids and even thinner for pseudoplastic fluids transition and laminar layers are neglected. Equation (9) for the center of the pipe can be written as:

$$\frac{u_m}{u^*} = f_1(Z, 1, n) = F_1(Z, n) \dots\dots\dots(16)$$

or from Equation (15),

$$\frac{u_m}{u^*} = P_n + \frac{V}{u^*} \dots\dots\dots(17)$$

Friction factor defined in Equation (2) can be written in terms of u^* as,

$$V \sqrt{\frac{\rho}{\tau_w g_c}} = \frac{V}{u^*} = \sqrt{\frac{2}{f}} \dots\dots\dots(18)$$

Combining Equation (17) and (18),

$$\sqrt{\frac{2}{f}} = F_1(Z, n) - P_n \dots\dots\dots(19)$$

It was shown that, at the outer part of the turbulent core, equation (13) for the wall region and equation (14) for the turbulent core are both assumed to be valid. Thus,

$$\frac{u}{u^*} = \frac{u_m}{u^*} - \frac{u_m - u}{u^*} \dots\dots\dots(20)$$

or in terms of the functions we use to define these parameters,

$$f_2(Z \xi^n, n) = F_1(Z, n) - f_3(\xi^n, n) \dots\dots\dots(21)$$

Considering the above relationship for a fixed value of n ,

$$f_{2n}(Z \xi^n) = F_{1n}(Z) - f_{3n}(\xi^n) \dots\dots\dots(22)$$

Specific form of $F_{1n}(Z)$ can be determined by a procedure involving partial differentiation of equation (22) with respect to Z and ξ^n . At the end of this derivation, they come up with:

$$\frac{u_m}{u^*} = F_{1n}(Z) = A_n \ln Z + B_n \dots\dots\dots(23)$$

where A_n and B_n are regarded as functions of n . Dodge and Metzner [6] states that, equation (23) does not contain ξ , and they therefore conclude that the equation is independent of the location and width of the overlapping region. Substituting equation (23) in to equation (19),

$$\sqrt{\frac{2}{f}} = A_n \ln Z + B_n - P_n \dots\dots\dots(24)$$

After determining the general relation for the friction factor, a relation between the friction factor and the Reynolds number is obtained by replacing Z and dividing by $\sqrt{2}$ as,

$$\sqrt{\frac{1}{f}} = 1.628A_n \log[N_{\text{Re}}^o (f)^{1-n/2}] - 0.4901A_n \left(1 + \frac{n}{2}\right) + \frac{B_n - P_n}{\sqrt{2}} \dots\dots\dots(25)$$

or

$$\sqrt{\frac{1}{f}} = A_{ln} \log[N_{\text{Re}}^o (f)^{1-n/2}] + C_n \dots\dots\dots(26)$$

where:

$$N_{\text{Re}}^o = \frac{D^n V^{2-n} \rho}{K} \dots\dots\dots(27)$$

$$A_{ln} = 1.628A_n \dots\dots\dots(28)$$

$$C_n = -0.491A_n \left(1 + \frac{n}{2}\right) + \frac{B_n - P_n}{\sqrt{2}} \dots\dots\dots(29)$$

Metzner and Reed's [5], and Dodge and Metzner's [6] assumption is based on using K' and n' parameters obtained under laminar flow within the wall region, to predict rheological constants K and n . To do this, the generalized Reynolds number for Power law fluids should be defined as;

$$(N_{\text{Re,gen}})_{\text{power-law}} = \frac{D^n V^{2-n} \rho}{8^{n-1} K [(3n+1)/4n]^n} \dots\dots\dots(30)$$

or

$$N_{\text{Re}}^o = \frac{1}{8} \left(\frac{6n+2}{n} \right)^n (N_{\text{Re,gen}}) \dots\dots\dots(31)$$

Thus, the friction factor can be expressed in terms of a generalized Reynolds number as;

$$\sqrt{\frac{1}{f}} = A_{ln} \log[N_{\text{Re,gen}} (f)^{1-n'/2}] + C_n' \dots\dots\dots(32)$$

where

$$C_n' = A_{ln} \log \left[\frac{1}{8} \left(\frac{6n'+2}{n'} \right)^{n'} \right] + C_n \dots\dots\dots(33)$$

In the last equation, expression A_{1n} , C_n , n' can be determined experimentally. The experimental measurements of Dodge and Metzner [6] include extensive data on Power-Law fluids which were use to obtain the following empirical relationships;

$$A_{1n} = \frac{4.0}{(n')^{0.75}} \dots\dots\dots(34)$$

$$C_n = \frac{-0.40}{(n')^{1.2}} \dots\dots\dots(35)$$

Inserting these relations to equation (16),

$$\sqrt{\frac{1}{f}} = \frac{4}{(n')^{0.75}} \log[N_{Re,gen} (f)^{1-n'/2}] - \frac{0.40}{(n')^{1.2}} \dots\dots\dots(36)$$

Dodge and Metzner [6] proposed another model for non-Newtonian fluid in turbulent flow. They derived a turbulent flow correlation by introducing apparent viscosity in Reynolds Number and by combining laminar flow equations for Newtonian and Power-Law fluids.

Another approach for predicting resistance to turbulent flow was introduced by Tomita [7]. He used similarity criteria and Prandtl's mixing length theory to define laminar and turbulent flow in Bingham Plastic and Power-Law fluids. First, by using similarity considerations, expressions for f and the Reynolds Number for Bingham Plastics in laminar flow is determined as;

$$f_B = \frac{D\Delta P g_c}{2\rho LV^2(1-c)} \dots\dots\dots(37)$$

and

$$N_{Re,B} = \frac{DV\rho}{\eta} \frac{(1-c)(c^4 - 4c + 3)}{3} \dots\dots\dots(38)$$

where c can be obtained from known values of V , R , τ_y and η that are obtained for laminar flow by using the following relation:

$$V = \frac{Rg_c\tau_y}{\eta} \left(\frac{c^4 - 4c + 3}{12c} \right) \dots\dots\dots(39)$$

This relation was obtained by balancing between shear and pressure forces acting on Bingham Plastic fluids in steady laminar flow. That is why Tomita called his model "Considering the turbulent flow as laminar flow". After applying

Prandtl's mixing length theory to obtain the relation between f_B and $N_{Re,B}$, and by using laminar flow expressions with numerical constants obtained for Newtonian fluids, the result is;

$$\sqrt{\frac{1}{f}} = 4 \log(N_{Re,B} \sqrt{f_B}) - 0.40 \quad \dots\dots\dots(40)$$

Using similarity considerations of laminar flow in smooth tubes for the Power-Law fluids results in,

$$f_p = \frac{2D\Delta P g_c (2n+1)}{3L\rho V^2 (3n+1)} \quad \dots\dots\dots(41)$$

and

$$N_{Re,P} = \frac{6[(3n+1)/n]^n D^n V^{2-n} \rho}{2^n [(2n+1)/n] K} \quad \dots\dots\dots(42)$$

After, again applying Prandtl's mixing length theory, and experimentally obtaining numerical constants for Newtonian fluids flowing through pipes with diameters ranging from 2" to 1/8" the following equation is obtained:

$$\sqrt{\frac{1}{f_p}} = 4 \log(N_{Re,P} \sqrt{f_p}) - 0.40 \quad \dots\dots\dots(43)$$

Although it gives comparable results with the experimental data, to apply this model rheological classification of the fluid model and rheological constants should be known. The model is restricted to Bingham Plastic and Power-Law fluids.

Clapp [8] obtained an integrated mean linear velocity, V , from the velocity profile in a turbulent core and obtained a relationship between friction factor and Reynolds Number:

$$\sqrt{\frac{1}{f}} = \frac{2.69}{n} - 2.95 + \frac{4.53}{n} \log[N_{Re,Cl} (f)^{1-n/2}] + 0.68 \left(\frac{5n-8}{n} \right) \dots\dots\dots(44)$$

where,

$$N_{Re,Cl} = \frac{D^n V^{2-n} \rho}{K 8^{n-1}} \quad \dots\dots\dots(45)$$

Nikuradse [9] introduced the effect of roughness and separated the curves for each level of tube roughness for turbulent flow of Newtonian fluids. He

observed that, in the fully turbulent region, friction factors are dependent on roughness but independent of Reynolds number. Experimental studies show that:

$$\sqrt{\frac{1}{f}} = 4 \log \frac{R}{e} + 3.48 \quad \dots\dots\dots(46)$$

Colebrook [10] recommends an empirical relationship for the transition region before fully developed turbulent flow of Newtonian fluids occurs, so that the friction factor is dependent on both roughness and Reynolds number;

$$\sqrt{\frac{1}{f}} = 4 \log \frac{R}{e} + 3.48 - 4 \log \left[1 + 9.35 \frac{R/e}{N_{Re} \sqrt{f}} \right] \quad \dots\dots\dots(47)$$

API equations [11] use effective viscosity while defining the regime of flow by using the Reynolds number. The Reynolds number for pipe flow can be calculated as follows:

$$N_{Re,P} = \frac{V_p D \rho}{\mu_{eff,P}} \quad \dots\dots\dots(48)$$

The friction factors for laminar and turbulent flow can be calculated as:

$$f_{P,lam} = \frac{16}{N_{Re,P}} \quad \dots\dots\dots(49)$$

$$f_{P,tur} = \frac{a}{(N_{Re,P})^b} \quad \dots\dots\dots(50)$$

where

$$a = (\log n + 3.93) / 50 \quad \dots\dots\dots(51)$$

$$b = (1.75 - \log n) / 7 \quad \dots\dots\dots(52)$$

The frictional pressure loss gradient is calculated from Fanning equation (in field units) as:

$$\frac{\Delta P}{L_m} = \frac{f_p V_p^2 \rho}{25.81 D} \quad \dots\dots\dots(53)$$

4.3.2 Turbulent Flow Of Non-Newtonian Fluids in Annuli

Although a large amount of experimental work has been done in circular pipes, there is a lack of experimental data for turbulent flow of non-Newtonian fluids through annular spaces. For this reason, while studying turbulent flow in annuli it was assumed that the relation between the Reynolds number and friction factor for pipe flow applies equally well to the other geometry. Thus, the only modification needed in the Fanning equation is to change the diameter to a more appropriate form.

Fredrickson and Bird [12] used conventional Newtonian f vs. Reynolds number charts that were derived for turbulent flow in smooth pipes. Consequently:

$$f = \frac{\Delta P g_c R_2 \left(1 - \bar{K}^2\right)}{L \left(1 + \bar{K}\right) \rho V^2} \dots\dots\dots(54)$$

Wilcox [13] suggested that knowing the radial position in the annulus at which the linear velocity is maximum could be used to determine an expression between friction factor and Reynolds number, but there is no method available for its prediction under non-Newtonian turbulent conditions.

API equations [11] for annular flow treat the annulus as a hydraulic diameter (OD-ID) and assumes smooth pipes, so the Reynolds number for annular flow change as follows:

$$N_{Re,P} = \frac{928 V_a (D_2 - D_1) \rho}{\mu_{ea}} \dots\dots\dots(55)$$

The friction factors can be calculated from the following equations as:

$$f_{a,lam} = \frac{24}{N_{Re,ann}} \dots\dots\dots(56)$$

$$f_{a,tur} = \frac{a}{(N_{Re,an})^b} \dots\dots\dots(57)$$

where

$$a = (\log n + 3.93) / 50 \dots\dots\dots(58)$$

$$b = (1.75 - \log n) / 7 \dots\dots\dots(59)$$

a and b obtained from experimental data. Frictional pressure loss is calculated by substituting the appropriate friction factor into the Fanning equation for the annulus and obtaining the friction loss pressure gradient as:

$$P_a / L_m = \frac{f_a V_a^2 \rho}{25.81(D2 - D1)} \dots\dots\dots(60)$$

Pilehvari [14] developed the concept of equivalent diameter and introduced the term ‘effective diameter’ which accounts for both the annular geometry and effects of a non-Newtonian fluid; thus it links Newtonian pipe flow and non-Newtonian annular flow. He proposed that the effective diameter for non-Newtonian pipe flow is equal to the diameter of a circular pipe that would have the identical pressure drop for flow of a Newtonian fluid when the viscosity is equal to the apparent viscosity and using the same average velocity as with non-Newtonian flow. Effective diameter can be shown as follows;

$$D_{eff} = 4ND / (3N + 1) \dots\dots\dots(61)$$

He extended the effective diameter definition to concentric annuli by including the effect of geometry as well. He defined effective diameter for non-Newtonian flow through a concentric annulus as the diameter of a circular pipe that would have identical pressure drop for flow of a Newtonian fluid with viscosity equal to the effective viscosity, and has a velocity equal to the non-Newtonian annular flow velocity. The effective viscosity is based on the average wall shear rate in the annulus.

4.4 RHEOLOGICAL CHARACTERIZATION OF DRILLING FLUIDS UNDER HIGH PRESSURE AND HIGH TEMPERATURE:

Rheological models provide assistance in characterizing fluid flow. While determining the flow regime by using the Reynolds number and predicting friction coefficients and parasitic pressure losses, rheological parameters such as viscosity, consistency index, density, yield stress control the fluid system and flow under consideration. All these parameters are subject to change under high pressure and high temperature conditions. For this reason, it is important to determine the response of the rheological model to wellbore conditions to fully understand the fluid performance and obtain accurate parasitic pressure loss results. Several investigators have attempted to model the effect of temperature and pressure on drilling fluid rheology through the shear rate history of the fluid.

Garvin and Moore (1970) [15] used a pipe rheometer to determine fluid properties from lower laminar flow to fully turbulent flow with temperatures up to 350 °F. Water-based drilling fluids were used as the testing fluid and concluded that the Bingham Plastic model gave a reasonable fit with the model in laminar flow, but data started to diverge under transition flow. They also concluded that plastic viscosity decreases with increasing temperature, yield point may increase

or decrease with increasing temperature depending upon the solid content of the fluid, power-law index (n) decreases with increasing temperature, and consistency index (K) increases with increasing temperature.

Methven and Baumann (1972) [16] analyzed the performance of oil based muds and invert emulsions at high temperatures. They used PVT data, computed downhole transient temperatures and Bottom-Hole Conditions (BHC) rheometer to determine rheological characteristics of the fluids. They concluded that density of oils varies inversely with temperature and directly with pressure, which is also a function of the relative density of the oil. Moreover, it was concluded oil based muds that contain asphalt were more stable under high temperatures.

McMordie, Bennett and Bland (1975) [17] used a BHC viscometer to determine the viscosity of the oil based muds at temperature up to 650 °F and pressure up to 20000 psig. They reported, the best model to describe the viscosity of oil based muds at constant temperature and pressure is the Power-Law model. Analysis showed that shear stress is directly proportional to pressure and inversely proportional to temperature. They modified the Power-Law model to depict these effects as:

$$\ln \tau = \ln K' + n \ln \gamma + AP + B/T \quad \dots\dots\dots(62)$$

The constants A and B must be determined experimentally.

McMordie, Bland and Hauser (1982) [18] investigated the change in density of water based and oil based drilling fluids in the pressure interval of 0-14000 psig and temperature interval of 70-400 °F under laboratory conditions. They concluded that the change in density of the drilling fluid is independent of its initial density; and oil based drilling fluids become denser at high pressure and temperature due to greater compressibility compared to water-base drilling fluids. Density at a given pressure and temperature was computed as:

$$\rho_1 = \rho_0 e^{0.000319N} - 1.064 * 10^{-5} P^{1.063} \quad \dots\dots\dots(63)$$

De Wolfe, Coffin and Byrd (1983) [19] studied the rheological changes of less toxic oil drilling fluids under pressure and temperature. They propose a general procedure for compiling a base of base-oil, laboratory prepared oil-base drilling fluids and oil-base drilling fluids used in the field. An HPHT rotational viscometer capable of temperature in the range of ambient to 500 °F and pressure in the range of 0-12000 psig, was used to investigate the rheological properties. Their research showed that, less toxic oils become more viscous as pressure is increased, but the viscosity differences among the oils tends to decrease with increasing temperature even if the pressure is increased. Moreover, temperature has the greatest effect on viscosity reduction below 200 °F.

Houwen and Geehan (1986) [20] compared rheological models for invert emulsion drilling fluids under pressures up to 1000 bar and temperatures up to 140 °C. They found that Herschel-Bulkley and Casson equations fit well with the experimental rheograms, but Casson's model is more reliable in terms of extrapolation purposes so that it is chosen as the rheological model. Then, they

developed exponential expressions to model temperature and pressure behavior of the Casson model. Their modified model is based on relations derived by Eyring for pure liquids and showed how changes in viscosity or yield point with change in pressure can be related to temperature or vice versa. As a result, they obtained viscosity and yield stress values as functions of pressure and temperature. The generalized form of these equations can be shown as:

$$\overline{VIS}(P,T) = A \exp\left(\frac{E}{RT} + \frac{YV_a P}{RT}\right) \dots\dots\dots(64)$$

API Recommended Equations [11] show the effect of temperature and pressure on viscosity as follows:

$$\mu_e(T_2) = \mu_e(T_1) \exp\left[\beta\left(\frac{T_2 - T_1}{T_1 T_2}\right)\right] \dots\dots\dots(65)$$

and

$$\mu_e(P_2) = \mu_e(P_1) \exp[\alpha(P_2 - P_1)] \dots\dots\dots(66)$$

Equation (65) is valid until a thermal decomposition or transition of any component in the drilling fluid take place. At this point drilling fluids do not follow any mathematical model. Equation (66) can be neglected for water based drilling fluids since they are only slightly compressible. On the other hand, pressure has a great effect on oil based drilling fluids and invert emulsions.

4.5 EXPERIMENTAL FACILITY

The Advanced Cutting Transport Facility loop located on the North Campus of The University Of Tulsa can function as a pipe viscometer. The loop consists of three rheology sections with nominal diameters of 2", 3" and 4". In addition to these, a drilling section is available to study the annular flow. The drilling section consists of a 6" external pipe and an inner 3.5" drillpipe. The drillpipe will be installed after the piping system constants and calibrations for the 6" section have been completed. All of the pipes are made of steel that tested to 3300 psig for not less than 30 minutes and not more than 60 minutes. The test sections are 65 ft in length. Five feet of pipe at both the entrance and exit are available for use as a quieting section between the pressure taps and the entrance or exit to the test section. Thus, a separation of 55 ft between pressure taps is available for measuring pressure drop values.

A Halliburton Model HT 400 triplex fracturing pump is currently used to circulate mud in the system. Its maximum operating pressure is 11,200 psia and it can give flow rates as high as 250 gpm when the system pressure is 1000 psia. Due to the nature of this piston-type pump, pulsation occurs on each stroke while it is pumping fluid. Since the data acquisition system is sensitive, this pulsation generates wavy data recordings. To counteract the pulsation effect, a pulsation

dampener was installed at the discharge end of the pump and it was observed that the pulsation effect no longer exists.

As seen in Figure 1, the test sections are connected in series so that the same flow rate is passing through all the test sections (2", 3", 4" and annular section). This may help to see the effect of diameter on the flow regime and to control the flow rate in all testing sections. However by adjusting the valves properly, parallel flow through 2" and 3" test sections can also be achieved. Moreover, again by adjusting valves, annular flow alone can be studied at various flow rates.

To measure the differential pressure loss through the sections, a Rosemount Model 3051CD Differential Pressure Transmitters were installed. They measure the differential pressures in the range of 0.5 inH₂O to 250 inH₂O with 0.075% accuracy. Static pressure in the system is measured by two ways. Liquid-filled Bourdon Tube Pressure Gauges that range between 0 and 2000 psig in 20 psig increments measure pressure on the system (while adjusting the back pressure with a choke). Moreover, these gauges are used to check whether data acquisition system is working properly or not by comparing the readings of the computer with the gauges. One of these gauges was installed just after the pump exit to the discharge line to see the system pressure. Another Bourden gauge was installed before the choke to observe and control the back pressure applied to the system and a third gauge was installed to the downstream part of the choke to see if choke is working properly. Static pressure distribution in the system is also determined by using Rosemount Model 3051CA Absolute Pressure Transmitters, which measure absolute pressures from 0.167 to 4000 psia with 0.05% accuracy. These transmitters were mounted to the middle of each test section and to the discharge line just after the pump exit.

Choke valves are used to control and fix the system pressure. Pressure in the system is increased by decreasing the flow area. This is accomplished by injecting N₂ to the seals that are present in the choke as flow restrictive elements.

Doppler Sonic flow meters, capable of measuring flow rates in the range of 0 to 450 gpm, are used to measure the volumetric flow rate in the system. Two Doppler Sonic flow meters were mounted to the 4" drilling fluid discharge line, 5 ft apart from each other to check if both are working properly.

Differential pressure transducers, absolute pressure transmitters and Doppler flow meters were connected to a computer located in the control room near the loop. The system pressures, differential pressures and flow rates can be measured, data can be stored and averaging intervals can be controlled using the data acquisition system. The data acquisition system utilizes LABViewTM software, which is very powerful for data storage and logging, real time display and on-line analysis.

4.6 EXPERIMENTAL TEST PROCEDURE:

First, drilling fluid rheological properties are measured using Model 3500 Fann rotational viscometer at low and high shear rates. From this data, a rheological model of the fluid under ambient conditions is determined.

Then, the Halliburton triplex piston pump is used to circulate drilling fluid through the system. It is desirable to circulate the fluid at high flow rates to make sure that the 6" pipe is full.

After all the air is removed from the system, the flow rate is adjusted to 300 gpm without any back pressure. Differential pressures from each test section, static pressures from the middle of each pipe and at the pump exit, and flow rate are recorded after stabilization and each time the flow rate is decreased by 50 gpm intervals.

When 50 gpm flow rate data were recorded, system is again brought up to 300 gpm and back pressure of 200 psig is applied to the system by injecting N₂. Data is taken after stabilization of the flow is established. Then, the flow rate is again decreased by 50 gpm intervals and after each reduction of the flow rate, back pressure of the system is kept constant at 200 psig by adjusting the choke.

After all the flow rate ranges for a given back pressure are analyzed, the flow rate is readjusted to 300 gpm and the back pressure specified for a particular test is increased by 200 psig.

Once high temperature capability is added to the system, the above procedure will be carried at intervals of 25 °F starting from ambient temperature of the fluids and ending with the maximum temperature that the heat exchanger can convey to the fluid (220 °F planned initially).

4.7 RESULTS AND DISCUSSION:

Experiments with water without Back Pressure

Preliminary Tests with water using Piston-Type Pump:

The first experiments with the ACTF were carried out to calibrate the devices and to check the repeatability of data recorded by the differential pressure transducers, absolute pressure transducers and flow meters. It was decided to use water as a testing fluid for calibration process. It was planned to install one of the flow meters to the 4" discharge line right after the exit of the pump to see the total flow circulating in the system and to install the other flow meter to the 3" test section. The flow rate in the 2" test section should be the difference between these two flow meter readings.

In calibration tests 2" and 3" pipes were connected parallel to give the same pressure drop along the same differential length. Results of these experiments are shown in Table-2. According to the flow meter readings most of the flow was passing through the 3" test section, but flow through the 2" test section does not show an increasing trend with increasing total flow rate of the system.

Comparison of the experimental data with the results from published models [21] (Figures 2-4) show that the differential pressure transducers are overestimating the pressure losses and there is no direct relation between the flow rate and pressure losses. Comparison of experimental pressure loss in the 2" and 3" test sections (Figure 5) show that there is no agreement in the readings of these devices either. Inaccuracy of the data may be due to errors in the calibration of the devices or due to accuracy of the devices. It is also possible that, since all the differential pressure transducers and static pressure transmitters were mounted

on top of the pipes through large diameter connection parts (weld-o-lets), additional turbulence may have been generated in the area where data was recorded. A close look at the experimental data suggested that, the piston displacement nature of the pump could also be affecting the data.

Preliminary Tests with water using Centrifugal Pump (W/O Back Pressure):

A centrifugal pump was used to diminish the effects of piston impact. In addition use of centrifugal pump makes it possible to check the accuracy of the flow meters since flow rate in this type of pump is set to a desired rate by using a Fisher control valve and measured by using a mass flow meter. To decrease turbulence, differential pressure transmitters and static pressure transducers were mounted to the middle of the pipes using small taps instead of large diameter connection parts (weld-o-lets). Six sets of data from four experiments were collected using the centrifugal pump to check the repeatability of the results and how they were compared with theoretical calculations. Results for each test section are shown in Table-3.

It can be seen that sonic Doppler flow meter readings are generally underestimating the actual flow rate. In some cases, the flow meter in the 3" test section was recording higher flow rates than the flow meter in the discharge line. It was concluded that, this might be due to the nature of the Doppler flow meter. Since water used in the test did not contain that much solid particle in it, this may have caused the discrepancy of sonic Doppler flow meters readings. However, the results show good repeatability and match the theoretical data within the accuracy range of the pressure devices (Figures 6-7). A small over-reading of experimental pressure losses is acceptable, because the theoretical calculations assumed smooth pipe. As seen in Figure (7) that differential pressure losses in the 2" and 3" pipes were almost the same. Repeatability in recordings decrease as flow rate increases because at higher flow rates the error range of the differential pressure transmitter increases (i.e. ± 6 inH₂O at 300 gpm). From this point of view, it may be concluded that data recordings are repeatable.

Determination of Roughness of 6" Pipe By Using Centrifugal Pump Experimental Data:

Since the flow meters were not recording reliable values, the only reliable flow meter data is given by the mass flow meter. For that reason, comparison of actual flow rates and theoretical flow rates was done only for the 6" pipe where total flow is passing through. The friction factor vs. Reynolds number plot is given in Figure 8. The relative roughness of the 6" pipe was determined to be approximately 0.00060 (Table-4). It can be seen that there are still some problems of low flow rate readings, which might be due to the inability to achieve flow stabilization. To check the validity of the roughness estimation in the 6" pipe, actual pressure losses were compared with theoretical calculations using the 0.00060 as the relative roughness of the pipe (Figure 9). Comparability of experimental and theoretical results were excellent.

Preliminary Tests with water using Piston-Type Pump with pulsation dampener: Since the piston type pump produced fluctuations in the data, a pulsation dampener was installed on the system to reduce the effect of strokes. To help control the flow rate, an rpm counter was installed on the pump.

Experiments using the dampener agree with the experiments using the centrifugal pump (Table 5). It was also observed in the experiments using the triplex pump that sonic Doppler flow meters were not working properly. The flow meter in the discharge line is underestimating the actual flow rate. The flow meter in the 3" test section gave sporadic results in all ranges of flow rate. After it is determined that the differential pressure transducers and absolute pressure transmitters are working properly, the second phase will begin.

Calibration of Differential Pressure Transducers without flow under Elevated Pressure:

To see the effect of back pressure on the differential pressure transducers, it was decided to measure the differential pressure loss in the system at various back pressures when there is no flow in the system. First of all, the valve that connects flow loop to the water tank is closed so that water circulation is prohibited. Then system pressure is increased by pumping fluid to ACTF through triplex pump, at very low flow rates (0-10 gpm). Differential Pressure Transducer recordings were taken at every 200 psig back pressure intervals. Fluctuations in differential pressure losses were observed in all test sections. Differential pressure losses are highest in the 3" pipe while pumping fluid to the system through triplex pump. In addition to these, it was observed that the differential pressure transducers recorded non-zero values when there was no flow in the system. The reason for this could be the fact that, it takes time for differential pressure transducers to stabilize and record the actual pressure loss in the system after a disturbance such as introducing flow to the system. Transducers responded to any kind of flow in the system. Even discharging fluid from a discharge tap that is installed in 6" pipe to relief the pressure, create a pressure loss in the system. In this case, transducer in the 6" pipe responded to the flow immediately. As a result, the differential pressure loss recorded by this transducer was higher with respect to the losses in other test sections.

Same calibration test was carried using a hand pump to see the effect of triplex pump on transducer recordings. Pressure of the loop is increased steadily with the hand pump. It was seen that, as magnitude of disturbance decreases, fluctuations in the differential pressure transducers also decreases. As a result, it took less time for transducer to stabilize and record the actual pressure loss in the system. Comparison of differential pressure transducer tests with hand pump and piston type pump can be seen in Table-6 and Fig. 10. The reason of having differences between measurements with hand pump and triplex pump is that, during the tests with the triplex pump, it was not waited enough for flow to become steady.

As a conclusion, it can be said that differential pressure transducers respond back pressures fairly good when there is no flow in the system. It was observed that, fair amount of time should pass for flow to stabilize. Only after

that, differential pressure transducers record better differential pressure loss. Because, piston nature of pump causes excess pressure losses while introducing flow to the system at a different rate.

Calibration of Differential Pressure Transducers with flow under Elevated Pressure:

After it has been determined that transducers are recording close to zero inches of H₂O when there is no flow in the system, flow was introduced. Calibration experiments were carried out for flow rates 50, 100 and 200 gpm with 200 psig back pressure increments up to 1000 psig back pressure.

Since the calibration fluid is water, that is an incompressible fluid, it was expected to have same differential pressure drop for each back pressure value. Of course there may be little variations due to accuracy of the transducers and viscosity changes of the water due to temperature, but this should be in the order of ± 1 inches of H₂O. However, it was observed that most of the time, the differential pressure losses increase with increase in back pressure and fluctuating when there is no pressure in the system. The increase was sometimes 5-10 times higher than the differential pressure loss measured at the previous back pressure. It was observed that, the Rosemount differential pressure transducer in 3" pipe was measuring irrelevant pressure losses. Honeywell transducer was installed in 3" pipe and duration of each flow was extended. It was seen that, the measurements are repeatable for all test sections for each flow rate and back pressure values. The repeatability of data decreases when back pressure is greater than 800 psig or smaller than 200 psig. It was also found that better repeatability was obtained under high flow rates. The reason of this is the fact that, the piston motion is effective in altering differential pressure loss recorded by transducers and strokes would be felt much severely when the flow rate is lower. The differential pressure losses are increasing in the order of 2-3 inches of H₂O with increasing back pressure when Honeywell differential transducer was used in 3" pipe. It is the case for recordings of the 4" pipe with the Rosemount differential pressure transducer as well. This may happen because of the accuracy of the transducers or unstability of the system pressure since water is expanding due to thermal expansion. Examples of differential pressure loss measurement at 200 gpm flow rate as a function of increasing back pressure are given in Figures 11, 12, and 13.

More calibration experiments should be carried to reach a better repeatability and decrease the increase of differential pressure loss with increasing back pressure. In addition to that,

4.8 CONCLUDING REMARKS

- Most of the turbulent flow models for non-Newtonian fluids is generally derived with the assumption that the fluids that are non-Newtonian in laminar flow, behaves Newtonian in turbulent flow. Previous investigators defined this Newtonian behavior by introducing different viscosity definitions to flow equations that were derived for laminar flow.

- Most of the experimental work done on turbulent flow have been based on small scale apparatus with diameters ranging between 1/8"-1' and lengths ranging between 1'-10'. However, such sizes do not reflect the field conditions and may produce unrealistic results for turbulent flow in pipes and annuli.
- Turbulent flow in annuli is not well defined yet and very few experimental data is available. This study may help to understand the mechanism of turbulent flow of non-Newtonian fluids in annular geometry.
- Most attempts to characterize the rheology of emulsions have used rotational viscometers. However, rheological model predictions from rotational viscometer reflects fluid behavior under laminar flow conditions. Therefore, it would be beneficial to study the rheological properties of drilling fluids in a pipe viscometer to examine the effect of cyclical variations in temperature and pressure and turbulence effects. Data obtained from pipe a viscometer and rotational viscometer will be compared for possible correlation among them. Such a comparison will be both very interesting and very informative.
- Although synthetic drilling fluids have advantages over water-base drilling fluids in terms of operational features (lubrication, shale inhibition, prevention of gas hydrates in deepwater offshore drilling), and advantages over conventional oil base drilling fluids in terms of environmental constraints, they are very sensitive to pressure and temperature changes. This may cause rheological instability problems in the well and make calculation of pressure losses difficult.
- Determination of rheological models of synthetic drilling fluids flowing in turbulent flow under high pressure and temperature will allow the prediction of pressure losses and equivalent circulating densities in the wellbore without using expensive tools like pressure while drilling (PWD) and measurement while drilling (MWD)
- We will attempt to find the best rheological model for a given mud system under high pressure and temperature and at both low and high shear rates. This type of rheological model would be very useful in the development of models simulating turbulent and laminar flow of synthetic based drilling fluids in pipes and annuli.

NOMENCLATURE

A	pressure constant
A'	constant in Arrhenius equation
A _n	a function of n, constant at constant n, dimensionless
a	friction factor constant
A _{1n}	1.628A _n , dimensionless
B	temperature constant
B _n	a dimensionless function of n
b	friction factor exponent
c	$\tau_y/\tau_w=r_p/R$
D	tube diameter, ft

D_1	inner annulus diameter, ft
D_2	outer annulus diameter, ft
E	least squares sum
e	height of roughness projections inside tube, ft
f	Fanning friction factor, dimensionless
g_c	conversion factor, 32.174 lbmassft/lbforcesec ²
K	fluid consistency index, lbmassec ⁿ⁻² ft ⁻¹
K'	consistency index at the wall, lbforcesec ^{n'} ft ⁻²
K	R_1/R_2
L_m	measured depth, ft
n	flow behavior index, dimensionless
N	generalized flow behavior index of Metzner and Reed
N_{Re}^0	$D^n V^{2-n} \rho / K$
ΔP	pressure drop, upstream minus downstream conditions, lbforce/ft ²
P	pressure, psig
P_a	pressure drop in annulus
P_n	a dimensionless function of n
R	tube radius, ft
R_1 and R_2	inner and outer radii of annulus, ft
u	local linear velocity in the x-direction at r or y , ft/sec
u^*	friction or shear velocity, ft/sec
u_m	maximum linear velocity (at tube centerline), ft/sec
V	mean linear velocity in the x-direction, ft/sec
V_a	average bulk velocity in annulus, ft/sec
Y	1, if VIS stands for plastic viscosity or Casson high shear viscosity
Y	Y_B or Y_C if VIS stands for YP or τ_Y
y	normal distance from tube wall $R-r$, ft
α	pressure constant
β	temperature constant
η	plastic viscosity, lbm/ft-sec
μ, μ_{eff}, μ_{ea}	viscosity, effective viscosity, effective viscosity in annulus lbm/ft-sec
ξ	y/R , dimensionless
ρ	density, lbmass/ft ³
ρ_0	density at 70 °F, 0 psig, lb/gal
ρ_1	density at T, P , lb/gal
γ	shear rate, sec ⁻¹
τ_{rx}	shear stress in x-direction on surface normal to r , lbf/ft ²
τ_w	shear stress at the wall of a tube, $D\Delta P/4L$, lbf/ft ²
τ_y	yield stress, lbf/ft ²

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TABLE 1- Synthetic Based Drilling Fluid Experimental Test Matrix (Pipe Viscometer)

Fluid Temperature, ° F	Back Pressure, psi	Flowrate, gpm
75	0-1400 (200 psi increments)	50-300(50 gpm increments)
100	0-1400 (200 psi increments)	50-300(50 gpm increments)
125	0-1400 (200 psi increments)	50-300(50 gpm increments)
150	0-1400 (200 psi increments)	50-300(50 gpm increments)
175	0-1400 (200 psi increments)	50-300(50 gpm increments)
200	0-1400 (200 psi increments)	50-300(50 gpm increments)

TABLE-2 Water Experimental Data Analysis Results (Piston Type Pump)

Total Q	Q(3" pipe)	Q(2" pipe)	DP @ 2"	DP @ 3"	DP @ 6"	DP @2" (Theo.)	DP @3" (Theo.)	DP @6 (Theo.)
GPM	GPM	GPM	inH2O	inH2O	inH2O	inH2O	inH2O	inH2O
67.1393617	60.870426	6.2689362	9.172979	31.51234	2.783191	0.977797739	7.328435324	0.33383807
146.9992857	129.72821	17.271071	28.05143	67.20607	4.618214	5.760610814	27.54929175	1.31561069
149.0016346	128.35481	20.646827	25.48625	68.5976	4.619038	7.873232924	27.04091692	1.34713170
166.7226829	146.00195	20.720732	32.47146	64.1239	4.214634	7.922617664	33.87878471	1.63989657
172.5686364	150.42909	22.139545	34.95182	62.86409	5.014545	8.896209876	35.69693039	1.74184304
186.0906452	157.98032	28.110323	37.02452	60.02871	4.416452	13.5106112	38.8915643	1.98766732
187.8828205	165.44462	22.438205	45.95462	55.09872	6.097179	9.107286401	42.16404644	2.02128766
194.9553846	165.11385	29.841538	44.58923	51.39846	5.627692	15.00019521	42.01663642	2.15631603
196.376	162.279	34.097	45.305	54.796	5.814	18.94144431	40.76235183	2.18388853
246.9615385	223.72385	23.237692	62.59615	35.43846	5.506154	9.682723701	71.49845426	3.26157270
250.5121739	229.61261	20.899565	72.03935	45.34	9.218043	8.042665097	74.82430654	3.34407657
258.33	226.8	31.53	72.16579	50.39789	9.706316	16.5168317	73.22771896	3.52883805
268.2892593	243.58926	24.7	79.27556	35.11111	9.007778	10.77406182	82.97588707	3.77034856
271.0660606	244.82909	26.23697	84.31091	77.63424	6.89	11.97453682	83.71638242	3.83890401
273.6404762	247.43143	26.209048	76.83333	61.97524	7.231429	11.95224439	85.2798009	3.90293520
276.6186441	250.53932	26.079322	84.58678	79.69373	7.519492	11.84890766	87.16316458	3.97757415
293.2955172	267.33414	25.961379	94.45828	74.59034	6.725172	11.75529086	97.64396455	4.4066671

Table-3

Water Experimental Data Analysis Results (Centrifugal Pump)

Flowrate	Q (3" pipe)	Q (2" pipe)	Q (6" pipe)	DP @ 2"	DP @ 3"	DP @ 6"	DP @ 6" (Theo.)
GPM	GPM	GPM	GPM	inH2O	inH2O	inH2O	inH2O
50	12.57361009	24.1780704	36.75168	4.097626	3.7475	0.138434	0.19931
100	33.73484903	31.3694552	65.1043	14.25403	13.107	0.694452	0.67039
150	117.7970759	17.1038437	134.9009	29.53702	27.646	1.514529	1.36297
200	166.2980754	15.5893234	181.8874	49.69468	46.959	2.628356	2.2549
250	207.380161	17.8123253	225.1925	74.90797	71.051	3.981836	3.33212
300	249.8542135	18.9676675	268.8219	104.3481	99.529	5.547072	4.58446
50	161.771519	-117.5683	44.20322	3.560973	3.5139	0.099082	0.19931
100	39.4680206	29.3533677	68.82139	15.18543	14.368	0.731441	0.67039
150	121.5964054	15.7554918	137.3519	31.12723	29.394	1.551745	1.36297
200	169.0273799	13.8507095	182.8781	53.19731	50.17	2.708817	2.2549
250	211.8311764	16.8830101	228.7142	79.90992	75.342	4.126478	3.33212
300	255.3570781	14.0847813	269.4419	110.4048	104.53	5.760876	4.58446
50	12.57272752	25.3997469	37.97247	3.916224	3.5212	0.136868	0.19931
100	23.78265643	42.3497585	66.13241	15.12185	13.718	0.707211	0.67039
150	124.188576	10.0597013	134.2483	32.37143	29.532	1.53686	1.36297
200	166.8607003	12.293111	179.1538	55.72592	50.45	2.655693	2.2549
250	213.4628357	9.09152647	222.5544	84.79527	77.438	4.069493	3.33212
300	261.4210243	6.72319586	268.1442	121.5681	111.39	5.840117	4.58446
50	443.7211654	-401.43942	42.28174	3.530617	3.1761	0.123681	0.19931
100	266.8212117	-205.00133	61.81989	14.40873	13.145	0.715561	0.67039
150	112.5976896	16.139349	128.737	32.30836	29.612	1.627631	1.36297
200	161.7744674	20.0392931	181.8138	56.2698	51.726	2.839828	2.2549
250	211.8569887	12.7638329	224.6208	83.86308	77.146	4.225969	3.33212
300	254.1369432	10.5381944	264.6751	116.8287	107.53	5.883346	4.58446

Table-4 Roughness Analysis of 6" Pipe

Flowrate GPM	Abs. Rough., E in	Rel. Rough, E/d
50	-0.013553488	-0.002352628
100	0.001817511	0.000315485
150	0.00352535	0.000611934
200	0.003589628	0.000623091
250	0.003399828	0.000590145
300	0.003116531	0.000540971

Table-5 Water Experimental Data Analysis Results (Triplex Pump with Dampener)

Flowrate GPM	Q (3" pipe) GPM	Q (2" pipe) GPM	Q (6" pipe) GPM	DP @ 2" inH2O	DP @ 3" inH2O	DP @ 6" inH2O	DP@ 6" (Theo.) inH2O
50	227.8770479	-183.02778	44.84926	4.134272	3.7203	0.137537	0.19931
100	259.1158916	-186.68075	72.43514	16.19205	14.712	0.729493	0.67039
150	171.8874283	8.93831484	180.8257	35.80491	32.698	1.6465	1.36297
200	174.6955907	9.98497131	184.6806	60.7854	55.675	2.84196	2.2549
250	219.4061444	7.41945165	226.8256	90.13184	82.621	4.265537	3.33212
300	262.9024834	6.08643632	268.9889	124.9855	115.27	6.025803	4.58446
50	412.7174763	-368.44396	44.27351	4.155672	3.7359	0.148098	0.19931
100	169.5164557	-99.085594	70.43086	16.42089	14.946	0.771785	0.67039
150	131.0216367	6.4100512	137.4317	36.09076	33.027	1.720963	1.36297
200	173.5973845	9.52323639	183.1206	59.94986	55.03	2.891803	2.2549
250	217.4440913	8.31143694	225.7555	90.43711	83.383	4.405633	3.33212
300	260.1329578	7.37128871	267.5042	126.8621	117.26	6.145712	4.58446
50	450.6860033	-405.86834	44.81767	3.905709	3.4725	0.13284	0.19931
100	230.11685	-154.47501	75.64184	15.57634	14.194	0.748547	0.67039
150	123.8044675	12.1484325	135.9529	34.86319	31.933	1.702834	1.36297
200	167.8762725	11.9156275	179.7919	58.82706	54.081	2.884349	2.2549
250	211.27049	11.61836	222.8889	89.59437	82.657	4.3866	3.33212
300	251.91883	14.19397	266.1128	125.5597	116.04	6.085689	4.58446

Table-6 Comparison of Diff. Press. Transducer Tests with Triplex and Hand Pumps

Back Pressure	Dploss @ 3" (Hand)	Dploss @ 3" (Pump)	Dploss @ 4" (Hand)	Dploss @ 4" (Pump)	Dploss @ 6" (Hand)	Dploss @ 6" (Pump)
0	-0.01078	-0.01217	-0.15098	-0.27867	-0.05235	0.088916
200	-0.00885	6.6104	-0.16904	2.3428	-0.03019	0.9904
400	-0.01255	0.263684	-0.15745	-0.20316	-0.01673	0.044737
600	-0.01073	3.338	-0.12951	0.512	-0.00634	0.274
800	-0.01039	3.888	-0.09868	0.813333	0.011974	0.489333
1000	-0.01018	8.3	-0.05991	2.3764706	0.020531	1.3552941
1200	-0.01122	0.1228571	-0.03113	0.2571429	0.032435	0.0828571
1400	-0.01007		0.00352		0.050592	0.496154
1500	-0.0101		0.029186		0.06601	
0	-0.01078		-0.15098		-0.05235	
200	-0.00885	3.571538	-0.16904	1.583077	-0.03019	0.496154
400	-0.01255		-0.15745		-0.01673	
600	-0.01073	4.583333	-0.12951	0.876667	-0.00634	0.482222
800	-0.01039	2.755714	-0.09868	0.477857	0.011974	0.297857
1000	-0.01018	4.352727	-0.05991	1.380909	0.020531	0.577273
1200	-0.01122	16.80083	-0.03113	5.576667	0.032435	3.151667
1400	-0.01007		0.00352		0.050592	
1500	-0.0101		0.029186		0.06601	
0	-0.01078		-0.15098		-0.15098	
200	-0.00885	1.42	-0.16904	-0.115556	-0.16904	0.002222
400	-0.01255	5.8775	-0.15745	1.235	-0.15745	0.6275
600	-0.01073	5.783333	-0.12951	1.295	-0.12951	0.764167
800	-0.01039	7.311429	-0.09868	1.947143	-0.09868	1.017143
1000	-0.01018	1.177857	-0.05991	0.173929	-0.05991	0.177857
1200	-0.01122	1.646667	-0.03113	0.449881	-0.03113	0.325
1400	-0.01007		0.00352		0.00352	
1500	-0.0101		0.029186		0.029186

Figure 1: Schematic Representation of Advanced cutting Transport Loop (ACTP) Piping System

Figure-6 Comparison of Experimental and Calculated Pressure Losses for 6" Pipe
(Centrifugal Pump, H2O Circulation, Parallel Flow)

**Figure-9 Comparison of Experimental and Calculated Pressure Losses for 6" Pipe
(Centrifugal Pump, H2O Circulation, Parallel Flow, E/d=0.00060)**

Figure-10 Comparison of Pressure Loss Readings obtained by Hand and Piston Type Pumps

**Figure 11- Differential Pressure Loss Measurement @ 200 gpm for Various Back Pressures,
3" Pipe**

**Figure 12- Differential Pressure Loss Measurement @ 200 gpm for Various Back Pressures,
4" Pipe**

Figure 13- Differential Pressure Loss Measurement @ 200 gpm for various Back Pressures, 6" pipe

5. STUDY OF CUTTINGS TRANSPORT WITH FOAM UNDER LPAT CONDITIONS

This study has been initiated in September 1998. The project proposal has been prepared and presented at the November 1998 Advisory Board Meeting of ACTF-JIP. The proposal was well received by ACTF and TUDRP member companies. A project progress report was presented at the May 1998 Advisory Board Meeting of ACTF-JIP. The research in this project included several preliminary tasks namely:

- a-) Establish contact with foam technology experts from industry. As part of these efforts, experts from Clearwater Company and Bachmann Inc. has been contacted. Several meetings were held discussing the various aspects of making and breaking foam solutions for drilling purpose. Samples of foaming and defoaming agents were obtained from these companies for preliminary laboratory testing purposes.
- b-) Conduct preliminary laboratory experiments to understand the mechanisms of making and breaking foams and the factors affecting foam quality.
- c-) Design and development of experimental set-up to be used for full-scale study of foam flow and cuttings transport with foam.

Following section includes report on the research progress made between November 1998 and October 15, 1999. Part of this report has already been presented at the May 10, 1999 Advisory Board Meeting of ACTF-JIP.

Project Title: “Cuttings Transport With Foam In Horizontal And Inclined Wellbores”

Investigator: M. Evren Ozbayoglu

Objectives

1. To investigate foam rheology and flow behavior in pipe and annulus.
2. 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.

5.1 INTRODUCTION

Inefficient cleaning of wellbore may cause severe problems, such as stuck pipe, lost circulation, high torque and drag, loose control on density, poor cement jobs, etc¹. A solution to solve the problem is to increase the annular drilling fluid velocity, which will decrease cuttings concentration in the annular space, but the increment of the annular fluid velocity is limited because of the erosion of the open hole section and the higher bottomhole equivalent circulating density applied to the formations. Studies indicated that if the flow rate is high enough,

the cuttings would be removed always for any kind of fluid, hole size and hole angle². However, it is impossible to use such pumps continuously because of physical limitations, and also wellbore erosion will not let to perform such an operation. The positive effect of drillpipe rotation on cuttings transport is not always applicable. Most of the variables, such as cuttings characteristics, inclination angle and eccentricity, can not be controlled. Theoretically, ROP is controllable, but it is usually kept on the highest possible value mostly because of economic reasons. Since drilling fluid parameters are subject to control, it is logical to solve cuttings transport problems by improving the drilling fluid. Solution can be obtained for the above mentioned problem if foam is used as a drilling fluid.

Foams consist of a continuous liquid phase, forming a cellular structure that surrounds and entraps a gas phase³. Foams are considered to be dry or wet, depending on the gas content. Wet foams have spherical bubbles with large amount of liquid between the bubbles, and dry foam bubbles are polyhedral in shape, with definite contact between the bubbles. Foams can have extremely high viscosity, in all instances their viscosity is greater than that of both the liquid and the gas that they contain. At the same time, their densities are usually less than one-half that of water. They are stable at high temperatures and pressures. So, by using foam as a drilling fluid, high viscosity of the foam allows efficient cuttings transport, and low density of foam allows underbalanced conditions to be established, and formation damage is minimized. Also, compression requirement is decreased. Foams are usually characterized by the quality (Γ), the ratio of the volume of gas and the total foam volume :

$$\Gamma = \frac{V_g}{V_g + V_L} * 100 \quad (1)$$

where Γ is the foam quality (%), V_g is the gas volume, and V_L is the liquid volume. In present research studies, foams are referred to be aqueous solutions with small amounts of surfactants, and quality is between 0.52 – 0.96.

Foam rheology has been studied to a limited extent, even less is known about cuttings transport with foam. Therefore, in this study a comprehensive analysis of cuttings transport with foam in inclined and horizontal wells will be conducted.

A comprehensive literature survey on rheology & flow behavior of foam, and cuttings transport in horizontal wells and directional wells will be performed in order to understand the effects of foam rheology and flow behavior on cuttings transport efficiency in inclined and horizontal wells. Experiments will be performed with and without cuttings to investigate the flow behavior and the rheology of foam, and to determine the relationship between foam properties and optimum hole cleaning for a specified ROP and inclination. The effect of cuttings on frictional pressure losses will be investigated and an empirical correlation for frictional pressure losses during foam flow in pipes and annuli with and without

cuttings transport will be developed. Finally, a computer program will be developed for determining the flowing bottomhole pressure for a given gas and liquid injection rate at any ROP and inclination.

5.2 LITERATURE REVIEW

5.2.1 Foam Behavior and Rheology:

Khan⁴ worked with a capillary tube viscometer, a modified rotational viscometer, and a vibrating reed viscometer to measure foam viscosity. He concluded that apparent viscosity increased linearly with foam quality at a given shear rate and the apparent viscosity of foam decreased with increasing shear rate. He defined foam neither as Bingham plastic, nor a pseudoplastic.

Mitchell⁵ investigated foam viscosity in capillary tubes for various foam qualities. He concluded that foam approximately behaves as a Bingham plastic fluid and foam viscosity depends on both quality and shear rate. Also, he observed that wall slippage effect does not exist when foam flows and if shear rate is constant, viscosity of foam increases with increasing quality.

Beyer et al⁶ formulated equations for foam flow in vertical pipes and annuli from laboratory and pilot-scale experimental data. They concluded that the liquid volume fraction is the principal independent variable that affects the foam flow behavior. The equations proposed account for slippage at the pipe wall and fluidity velocity components.

Blauer et al⁷ proposed that for predicting frictional losses in laminar, transient and turbulent flow regimes for foam flow, Reynolds number and Fanning friction factors can be calculated by using “effective foam viscosity”, actual foam density, average foam velocity, and true pipe diameter. It was observed that, the relation between the Reynolds number and Fanning friction factor for foam is identical with the single phase fluids. They also concluded that, foam behaves as a single-phase Bingham plastic fluid.

Sanghani⁸ performed experiments to determine foam flow characteristics with concentric annular pipe viscometer. He concluded that the foam behavior is power-law, pseudo-plastic, below shear rates of 1000 1/s, and at a given quality, effective viscosity decreases with increasing shear rate. He also concluded that most foam drilling operations can be carried out in laminar flow region because of foam's low density, high viscosity and high carrying capacity, if bottomhole quality is not less than 0.55. From tables given by Sanghani one can easily determine all power-law foam characteristics such as consistency index, flow behavior index, effective viscosity as a function of quality and foam flow rate.

Heller and Kuntamukkula⁹ reviewed the foam rheology literature. They reported that some experimental results, like apparent viscosity values, are geometry dependent. According to them, this dependence is a consequence of a flow regime that involves little or no shearing of the bulk foam itself. Therefore, they

proposed two critical requirements as standards; i) the data must be reproducible; ii) the observed rheological behavior should be unique and independent of the type of viscometer used or of its size. They concluded that the concept of apparent viscosity as a measure of the resistance to the flow of foam in pipes seems to be only qualitatively useful because of the differences in the mechanism of flow that become operable at different scales of bubble size and flow channel dimensions.

Cawiezel and Niles¹⁰ observed the influence of temperature, pressure, quality and shear rate on the rheological properties of foam. According to them, rheological behavior of foam fluid is a yield-pseudoplastic fluid and it can be described by Herchel-Bulkley method. They concluded that, as foam quality increases, the foam apparent viscosity increases and it becomes more pseudoplastic. Also, at higher foam qualities, the apparent viscosity increases exponentially with increase in foam quality. They mentioned that an increase in temperature significantly decreased the apparent viscosity of the foam up to a critical temperature, after which little change is observed. They observed a significant increase of the viscosity in the foam fluid as the pressure increases at low shear rates.

Valkó and Economides¹¹ investigated flow behavior of foamed polymer solutions in large-scale vertical tubes and developed constitutive equations. Their approach was based on the “volume equalization principle” in which they defined power law and bingham plastic models again by using a new variable, called the specific volume expansion ratio, which is the ratio of the specific volume of base liquid to specific volume of foam;

$$\varepsilon_s = \frac{\rho_L}{\rho_F} \quad (2)$$

where ε_s is the specific volume expansion ratio, ρ_L is the base liquid density, and ρ_F is the foam density. Both constitutive equations, volume equalized power law, and volume equalized Bingham plastic, have a simple form with the use of the specific volume expansion ratio. The volume equalized power law equation is given by :

$$\tau = \left[K \varepsilon_s^{1-n} |\dot{\gamma}|^{n-1} \right] \dot{\gamma} \quad (3)$$

where the parameters K and n are constants for the foams of a given gas-liquid pair at a given temperature, τ is the shear stress, and $\dot{\gamma}$ is the shear rate. The volume equalized Bingham plastic is given by :

$$\tau = \left[\frac{\tau_o \varepsilon_s}{|\dot{\gamma}|} + \mu_p \right] \dot{\gamma} \quad \begin{matrix} |\dot{\gamma}| > \tau_o \varepsilon_s \\ \gamma = 0 \end{matrix} \Rightarrow \tau > \tau_o \varepsilon_s \quad (4)$$

where τ_0 and μ_p are constant for a given gas-liquid pair at constant temperature. An interesting graphical consequence of the volume equalizing principle is that the plot of wall stress divided by the specific volume expansion ratio, as a function of the shear rate divided by the specific expansion ratio, results in a unique curve which might serve as a replacement to the flow curve in incompressible flow. According to Valko and Economides, the advantages of the new model are; in isothermal foam flow, friction pressure loss due to friction can be calculated easily because volume equalized friction factor is constant along the flow; and pressure loss estimation is easy because of simple form and small number of parameters.

Enzendorfer¹² investigated foam viscosity using a pipe rheometer. The rheology was determined in pipes of various diameters pipes at a given pressure, temperature and quality. Enzendorfer reported that flow curves showed marked dependence on the diameter of the pipe. The concept of apparent slip was used to explain the phenomena. Mooney's¹³ classical slip correction was not applicable, but a method developed by Jastrzebski¹⁴ provided a consistent means of apparent slip correction. In this way, a small-scale pipe viscometer can be used to characterize the bulk foam rheology. The geometric interpretation of the two slip correction methods revealed the possible reason for the difference of their performance. The corrected flow curve corresponding to a given pressure and quality shows approximately power-law behavior with no clear indication of yield stress. Viscosity increased with increasing quality. The slip corrected measurements were interpreted in the framework of the volume equalization principle⁸. The fact that the individual flow curves form one master curve when volume equalization is applied means that this scaling gives the right dependence of the rheology of foam on the volumetric relationship of gas and liquid.

Gardiner et al¹⁵ examined the rheological properties of compressed-air foams and contained velocity profiles in foams flowing through straight horizontal tubes. They showed that a master equation can be derived from the experimental data to account for a range of expansion ratios and pressures of polyhedral-structure foams. Results were corrected for wall slip using Oldroyd-Jastrzebski's method²⁸. They observed that all data points aligned themselves along two master curves, depending on foam texture, whether foam had bubble cells, or polyhedral cells.

Krug and Mitchell¹⁶ developed charts to predict volumetric requirements for foam drilling operations. Foam behavior characteristics were calculated from Mitchell's rheology model. Total pipe length was divided into incremental lengths and the foam properties were assumed to be constant in each incremental length. No corrections were made for the gas compressibility or the friction of flow. They assumed that bottomhole fluid velocity for particle transport is constant. This assumption can lead to sticking of BHA if settling velocity is higher; on the other hand it predicts excess volumetric requirements.

Lord¹⁷ developed an equation of state for foam. This related foam density to pressure, temperature, liquid density, and the gas mass fraction, presuming real gas behavior.

where

$$\rho_F = \frac{P * M}{P * M * (W_L * SV_L + W_S * SV_S) + W_G * Z * R * T} \quad (5)$$

m is mass, M is molecular weight of gas, P is the absolute pressure, R is the gas

$$W_G = \frac{m_g}{m_g + m_l + m_s}$$

$$W_L = \frac{m_l}{m_g + m_l + m_s}$$

$$W_S = \frac{m_s}{m_g + m_l + m_s}$$

constant, SV_L is the specific volume of liquid, SV_S is the specific volume of solid, T is the absolute temperature, W_g is the mass fraction of gas, W_L is the mass fraction of solid, and Z is the gas compressibility factor. A mechanical energy balance for the circulating system related the pressure at the entrance and exit of the circulating system in terms of the equation of state. Frictional pressure losses were estimated by assuming a constant friction factor throughout the system, taken as the average of friction factors computed at the inlet and the outlet. This model requires numerical solution, if flowing pressures are to be predicted, and the friction factor has to be carefully selected. The model was developed for hydraulic fracturing treatments and accurately predicted downhole pressures when proppant-laden foam was pumped down a well.

Okpobiri and Ikoku¹⁸ developed a semi-empirical correlation to determine frictional pressure losses due to the solid phase in foam flow and by using this correlation, they predicted the minimum volumetric requirements for foam drilling operations. Experimental results showed that the friction factor of foam flow transporting cuttings can be expressed as the sum of friction factor of the neat foam slurry plus that due to solids. For a constant flow Reynolds number, they observed an increase in friction pressure losses with an increase in solid mass flow rate. They assumed that all foam drilling operations are performed in laminar flow region, and foam qualities varying with varying pressure are between 0.55 and 0.96. To keep quality between these boundaries, their model suggests the application of annular backpressure. They concluded that volumetric requirements increase with increasing particle size. Also, they observed that increases in penetration rate cause only minor increases in volumetric requirements.

Spörker et al¹⁹. designed a system for investigating downhole foam rheology. Experiments were carried out on an industry-scale vertical flow-loop in order to observe the interactions between gravitational, frictional and other factors, such as gas gravity, etc. They used an improved version of Lord's pressure drop equation for two-phase downward flow considering gas compressibility factor not to be constant. The final form of the equation presented differs from Lord's equation because pressure is used instead of specific volume, and the solution for pressure drop is not complicated as Lord's method. In case of incompressible fluid, not like Lord's equation, the modified equation reduces to the Fanning pressure drop equation. The Fanning friction factor was used as a main factor in evaluating the results.

Liu and Medley²⁰ introduced a new mechanistic model that calculates varying Fanning friction factors along the flow path using the well-known incremental technique. They used an equation of state for real gas and a mechanical energy balance to determine the required characteristics, such as pressure profile, foam density and quality as a function of depth and cuttings concentration. Results are calculated with numerical methods. Inputs of the model are injection pressure, backpressure, and gas and liquid injection rates. Friction factors are calculated by means of an improved version of Lord's pressure drop equation and Spörker's method. They developed a computer program to be used in the field.

Foam Hydraulic Models

For a better understanding of cuttings transport phenomena with foam, the foam rheology must be investigated properly. The hydraulic models given below are used in the computer program for the determination of pressure losses due to friction in pipes.

Blauer et al⁷

They proposed that it was possible to determine the pressure losses due to friction for foam flow by using Reynolds number and Fanning friction factor if effective foam viscosity, actual foam density, average velocity and "true pipe diameter" concepts are applied. Their starting point was the relation of foam quality and the viscosity of foam. They assumed that foam behaves as Bingham plastic.

The Buckingham-Reiner equation for laminar flow of Bingham plastic fluids in pipes is given as

$$Q = \frac{\pi \Delta P D^4 g_c}{128 \mu_e L} \quad (6)$$

The Haigen-Poiseuille equation for Newtonian laminar flow in pipes is given as

$$Q = \frac{\pi \Delta P D^4 g_c}{128 \mu_p L} \left(1 - \frac{4}{3} \frac{\tau_y}{\tau} + \frac{1}{3} \left(\frac{\tau_y}{\tau} \right)^4 \right) \quad (7)$$

For the “Newtonian turbulent flow” relationships to be valid for a Bingham plastic fluid, both equations must be equal to each other. So, effective viscosity for Bingham plastic foam can be defined as

$$\mu_e = \mu_p + \frac{g_c \tau_y D}{6v} \quad (8)$$

They used the same method that Mitchell⁵ used to show average velocity and quality of foam can be derived by using a mass balance and real gas law. They used the table tabulated by Krug¹⁶ for the determination of the plastic viscosity and yield strength.

The foam density is defined by

$$\rho_f = \rho_l (1 - \Gamma) \quad (9)$$

The pressure loss gradient is determined by using Buckingham-Reiner equation.

$$\frac{\Delta P_f}{\Delta L} = \frac{128 Q \mu_p}{\pi D^4 g \left(1 - \frac{4}{3} \frac{\tau_y}{\tau_w} \right)} \quad (10)$$

*Sanghani*⁸

The main difference between Sanghani's work and Blauer et. al.'s work is that, he explained the foam behavior as Pseudo Plastic. He developed a table that shows the quality dependence on model parameters, K and n.

The effective viscosity is defined by

$$\mu_e = K \left(\frac{3n+1}{4n} \right)^n \left(\frac{8V}{D} \right)^{n-1} \quad (11)$$

The density of foam differs from Blauer's work by including the effect of gas phase

$$\rho_f = \rho_l (1 - \Gamma) + \rho_g \Gamma \quad (12)$$

The pressure loss gradient is calculated by using the empirical equation

$$\frac{\Delta P_f}{\Delta L} = \frac{4K}{D} \left(\frac{8(3n+1)Q}{\pi m D^3} \right)^n \quad (13)$$

*Beyer et al*⁶

They described the composition of the foam at any temperature and pressure by the liquid volume fraction, which is

$$LVF(T, P) = \frac{VOL_L}{VOL_L + VOL_G(T, P)} \quad (14)$$

where VOL_L is the liquid volume fraction in the foam, and VOL_G is the gas volume fraction in the foam.

According to the pilot-scale experiments, total velocity (v_T) is composed of slip component (v_S) and a fluidity component (v_F)

$$v_T = v_S + v_F \quad (15)$$

The slip velocities calculated from experimental data were defined by LVF and τ_w for these conditions :

For $\tau_w \leq 0.0024$ psi

$$v_S = 25.8LVF \frac{\tau_w}{0.0024} \quad 0.02 \leq LVF \leq 0.1 \quad (16)$$

$$v_S = (1.1 + 14.8LVF) \frac{\tau_w}{0.0024} \quad 0.1 \leq LVF \leq 0.25 \quad (17)$$

For $\tau_w > 0.0024$ psi

The velocity of a Bingham fluid in a circular pipe of diameter D is given by

$$v_S = 25.8LVF + 357(\tau_w - 0.0024) \quad 0.02 \leq LVF \leq 0.1 \quad (18)$$

$$v_S = 1.1 + 14.8LVF \quad 0.1 \leq LVF \leq 0.25 \quad (19)$$

$$v = \frac{144D\tau_w}{8\mu_o} \left[1 - \frac{4}{3} \left(\frac{\tau_y}{\tau_w} \right) + \frac{1}{3} \left(\frac{\tau_y}{\tau_w} \right)^4 \right] \quad (20)$$

The fluidity of foam is expressed as

For $\tau_w < (4/3)\tau_y$

$$v_F = 0 \quad (21)$$

For $\tau_w > (4/3)\tau_y$

$$v_F = \frac{144D}{8\mu_o} \left[\tau_w - \frac{4}{3}\tau_y \right] \quad (22)$$

The Bingham viscosity of the foam is given by

$$\mu_o = \frac{1}{7200LVF + 267} \quad (23)$$

$$\mu_o = \frac{1}{2533LVF + 733} \quad (24)$$

So, the definitions are combined together to give explicit functions, Ψ , for the frictional pressure gradient versus v_T , LVF, and D

$$\left(\frac{dP}{dL} \right)_f = \frac{4\tau_w}{D} = \Psi[v_T(T, P), LVF(T, P), D] \quad (25)$$

*Valko and Economides*¹¹

The basic idea of Valko and Economides' model is to define constitutive equations for non-Newtonian compressible fluids by using the invariance property of Reynolds number (constant friction factor) that is valid for incompressible Newtonian, compressible Newtonian and incompressible non-Newtonian fluids. They defined a variable called "specific volume expansion ratio" (eq.2), which they used instead of "foam quality" for the characterization of the foams.

All the density-dependent parameters are defined with respect to liquid density by using this variable. For isothermal conditions, if the linear velocity is $u = \epsilon u_o$, where u_o is the linear velocity of pure liquid, in order to keep the Reynolds number constant along the pipe, the ratio τ/ϵ should be kept constant. The "Volume Equalized Principle" requires

$$\frac{\tau}{\epsilon} = f\left(\frac{u}{D\epsilon}\right)$$

The principle states that all volume equalized shear-stress volume equalized shear-rate points obtained in different qualities and different geometry lie on one curve in isothermal conditions. When “Volume Equalized Principle” is applied to power law (eq.3). By using the model parameters K and n, the pressure drop can be calculated if the foam density is known at the inlet of the pipe.

The VE Reynolds number is derived as

$$N_{Re\ VE} = \frac{1}{K} D^n u^{2-n} \rho \epsilon^{n-1} \quad (26)$$

The VE Fanning friction factor is

$$f_f = \frac{16}{N_{Re\ VE}} \left(\frac{1}{8} \right) \left(\frac{6n+2}{n} \right)^n \quad (27)$$

For isothermal steady circular horizontal pipe flow of compressible fluids, the mechanical energy balance is given by

$$\frac{dp}{\rho} + u du = - \left(\frac{f_F}{m} u^2 \right) dx \quad (28)$$

By using the Virial Equation of state, gas mass and gas behavior dependent variables are defined as

$$a = w_g \frac{RT}{M_g} \quad (29)$$

$$b = \frac{w_g RTB'}{M_g} + (1 - w_g) \frac{1}{\rho_l} \quad (30)$$

$$c = \frac{4(m_g + m_l)}{D^2 \pi} = u \rho \quad (31)$$

The foam density is described as

$$\rho = \frac{p}{a + bp} \quad (32)$$

The superficial velocity derived from continuity is

$$u = \frac{c}{\rho} = \frac{ac}{p} + bc \quad (33)$$

and

$$du = -\frac{ac}{p^2} dp \quad (34)$$

So, differential mechanical energy balance equation for horizontal flow becomes

$$\frac{dP}{dx} = -\frac{1}{D} \frac{2f_f b^2 c^2 p^3 + 4f_f abc^2 + 2f_f a^2 c^2 p}{bp^3 + ap^2 - abc^2 p - a^2 c^2} \quad (35)$$

*Sporker et al*¹⁹

They developed a model for pressure loss estimation during vertical flow of multiphase fluids. In this study, they separated upward and downward flow, and derived the equations for both cases. For the computer simulator, the upward equations are adjusted for horizontal flow by neglecting the gravitational effects. The differential mechanical energy balance is defined by

$$vdP + udu = -\left(\frac{2f_f}{D} u^2\right) dx \quad (36)$$

The specific volume of foam is defined as

$$v = w_g v_g + (1 - w_g) v_{inc} \quad (37)$$

where w_g is the mass fraction of gas, $m_g/(m_g + m_{inc})$, v_{inc} is the incompressible specific volume and is constant. Specific volume of gas is defined as

$$v_g = \frac{RT}{M_g} \left(\frac{1}{p + p^e} + B' \dots \right) \quad (38)$$

where the term in parenthesis is the compressibility factor.

So, equation of state for the foam is obtained as

$$v = w_g \frac{RT}{M_g} \left(\frac{1}{p + p^e} + B' \right) + (1 - w_g) v_{inc} = \frac{a}{p} + b \quad (39)$$

where

$$a = w_g R \frac{T}{M_g} \quad (40)$$

$$b = \frac{w_g RTB'}{M_g} + (1 - w_g) v_{inc} \quad (41)$$

The linear velocity is obtained from continuity equation, and defined in terms of specific volume as

$$u = cv = \frac{ac}{p} + bc \quad (42)$$

where

$$c = \frac{4(w_g m_g + (1 - w_g) m_{inc})}{D^2 \pi} \quad (43)$$

$$du = -\frac{ac}{p^2} dp \quad (44)$$

so, substituting into mechanical energy balance gives

$$\frac{dp}{dx} = -\frac{1}{D} \frac{(2f_f b^2 c^2)p^3 + 4f_f abc^2 p^2 + 2f_f a^2 c^2 p}{Dbp^3 + ap^2 + (-abc^2)p + (-ac^2)} \quad (45)$$

*Gardiner et al*¹⁵

They used “Volume Equalized Principle” proposed by Valko & Economides¹¹. Assuming an isothermal flow and change of axial velocity on radial velocity to be negligible, they assumed that in short segments of pipes, pressure gradient, temperature and density of foam are constant, and they applied Haigen-Poiseuille formula for power law.

Applying the momentum balance equation for horizontal pipelines and using the concept of volume equalization with shear stress and manipulation yields

$$\left(-\frac{du}{dr}\right)^n = \frac{\varepsilon^{n-1}}{2k} \left(-\frac{dp}{dx}\right) r \quad (46)$$

Integration for the boundary condition $u(r=R) = u_{slip}$ gives

$$u = u_{slip} + \frac{n}{n+1} \left(\left(-\frac{dp}{dx} \right) \frac{R^{n+1} \varepsilon^{n-1}}{2k} \right)^{\frac{1}{n}} \left(1 - \left(\frac{r}{R} \right)^{\frac{n+1}{n}} \right) \quad (47)$$

Integration of the above equation over a cross-sectional area gives

$$Q_{calculated} = 2\pi \int_0^R u r dr = \pi R^2 \left\{ u_{slip} + \frac{n}{3n+1} \left[\left(-\frac{dp}{dx} \right) \frac{R^{n+1} \varepsilon^{n-1}}{2k} \right]^{\frac{1}{n}} \right\} \quad (48)$$

Slip velocity, u_{slip} , is based on Oldroyd-Jastrzebski correlation.

$$\beta = \frac{\beta_c}{D} = \frac{u_{\text{slip}}}{\tau_w} \quad (49)$$

The observed flow rate incorporates the true flow rate due to the flow of foam itself and a component due to apparent slip:

$$Q_{\text{observed}} = Q_{\text{true}} + Q_{\text{slip}} = Q_{\text{true}} + \left(\frac{\pi D \tau_w \beta_c}{4} \right) \quad (50)$$

5.2.2 Cuttings Transport:

There are many studies available for cuttings transport with conventional fluids, but only a few studies are reported about air drilling and cuttings. However, there are even less studies performed on cuttings transport with foam. Okpobiri and Ikoku¹⁸ presented a semi-empirical model for predicting frictional losses due to the solid phase in solids- foam slurry flow. Also, they developed a theoretical model for predicting the pressure drops across the bit for foam. In the literature, no studies were found on cuttings transport with foam in horizontal and inclined wellbores.

Martin et al.²¹ performed a study for observing the influence of inclination in wellbore cleaning. They concluded that influence of inclination is apparent as soon as the well has 10° deviation, and removal of cuttings is more difficult in slanting zones; i.e. angles between 30° and 90°. They observed that thixotropy of a drilling fluid is very unfavorable for the slanted zones, while, high viscosity of the drilling fluid is favorable for cleaning at vertical parts, but reduces the transfer capability in slanted parts.

Gavignet and Sobey²² proposed a model for determining the mechanisms controlling the thickness of a cuttings bed that occurs in highly deviated wells. They observed that at high flow rates the bed has negligible thickness. As the flow rate decreases the bed thickness increases slowly until a critical mud flow rate is reached, at which time a different bed thickness is observed. Also, they mentioned that there is a critical angle of inclination at which a bed will suddenly form for a fixed flow rate, and once the bed is formed, further increase in inclination angle has a minor effect. They concluded that drillpipe eccentricity, particle size, hole diameter and pipe diameter have a large effect on bed thickness.

Larsen et al.²³ developed a new design model for hole angles from 55° up to 90° that enables the user to select the proper hydraulic parameters. The model not only predicts the critical transport velocity and the annular cuttings concentration, but also the cuttings bed thickness when the flow rate is below the critical value.

Martins and Santana²⁴ presented a mechanistic model to describe the stratified flow of solid and non-Newtonian fluid mixtures in horizontal and near horizontal

eccentric annuli. Their model consists of two layers: a heterogeneous suspension and a compact bed of solids. They concluded that using large-diameter drill pipes, increasing the fluid density and increasing the flow rate improves cleaning of the well.

According to Clark², the transport of cuttings from the drill bit to the surface depends mostly on wellbore angle. In this study, it is observed that for high angles, where a stationary cuttings bed can form, transport occurs by rolling mechanism. Lifting is the mechanism where a churning and moving bed can form at intermediate angles. At angles close to vertical, particle settling determines transport.

Belavadi and Chukwu²⁵ constructed a well simulation unit and performed a set of tests to observe the effects of fluid and cuttings densities. They observed that an increase in the fluid flow rate at higher fluid densities increases the transport ratio. Also, pipe rotation enhances removal of cuttings at high flow rates with high density muds. According to their experiments, a small increase in fluid density-viscosity ratio causes the transport ratio to decrease rapidly.

Pilehvari, Azar and Shirazi¹ reviewed the developments in cuttings transport through the mid 1990's, and addressed future research needs on cuttings transport in horizontal wells. They suggested that a comprehensive and a proven model still did not exist, and to develop one would require many laboratory research and field studies.

Nguyen and Rahman²⁶ presented a three-layer hydraulic program for cutting transport in deviated and horizontal wells. Their model consists of three components: a bed of particles of uniform concentration, a dispersed layer, and a fluid-flow layer, which consists of pure fluid or a turbulent suspension. A critical fluid velocity, average cutting velocity and annular cuttings concentration is predicted empirically in wells with deviations between 55° and 90° from vertical. It was concluded that an increase in fluid viscosity improves cuttings transport; however, this effect is relatively minor compared to other factors such as mud weight, cuttings density, etc.

Sanchez²⁷ studied the feasibility of using a simulator of annular flow to model cuttings bed erosion in highly inclined wells. He observed the effect of geometry and eccentricity by identifying the detrimental effect of creating a gap between the cuttings bed and the drillpipe. He concluded that if the gap is narrowed, the mud velocity under the drillpipe and hence, the interfacial shear stress are reduced. The results of his work showed that a simulator ("Annflow") could be used to describe the qualitative effects of rheological and geometrical parameters.

5.3 EXPERIMENTAL FACILITY

Experiments will be performed on TUDRP's low pressure-ambient temperature flow loop, which has been modified for investigating liquid and aerated mud flow with cuttings. The flow loop is approximately 100 ft. long and it consists of an 8 in. inner diameter transparent casing with a 4.5 in diameter drillpipe. The drillpipe can be rotated up to 200 rpm. One end of the flow loop is attached to a movable platform while the other is connected to a pulley, which enables the user to incline the loop at angle between 10° to 90° from vertical. A 75 HP centrifugal mud pump (maximum capacity 750 gpm) is used with a Fisher control valve (V150-rotary control valve) to provide a controlled circulation of mud through the loop. A compressor (with working capacity 0-125 psi, 0-1600 scfm) is used to supply compressed air. The air is compressed to a particular pressure and carried to the bottom of the test section, where it is mixed with the mud at the entrance of the flow loop. The flow rates of both the gas and liquid phases are measured using mass flow meters (Micro-motion Inc.). Cuttings are injected into the bottom of the annular test section, where they merge with the main flow. The cuttings fall into a rotating auger system, which moves them toward the wellbore test section inlet. A high-capacity air vent valve is fixed at the top of the cuttings injection system. This equipment provides means of eliminating the trapped air at the top of the cuttings injection tank. The injected cuttings are automatically replaced with liquid to maintain a full hopper. Pressure taps located at the two ends of the flow loop measure differential pressure using a Honeywell differential pressure transducer. A control room located near the test section contains the data acquisition system. The control and measurement of the flow rates of both phases, air and liquid, control of drillpipe rotation and flow loop inclination angles, and control of quick-closing valves for holdup measurement can be done from the control room. The loop pressure, temperature and densities of both phases can also be measured using the data acquisition system. A "LABTECH Control" data acquisition software is currently being used for data logging and storage, real-time data display, on-line analysis, process monitoring, etc. Installation of a newer data acquisition software called "LABVIEW" is in progress.

The TUDRP LPAT flow loop needs to be modified for foam flow with cuttings. Since the liquid rates will be lower for foam flow, a more accurate control valve is required in order to measure the liquid flow rate. The liquid + surfactant mixture and gas will be mixed in a static mixer to generate foam. Komax 4M static mixer will be used for this purpose. In order to determine the rheological properties of foam, a pipe viscometer system will be constructed. The pipes are acrylic transparent ones with 2 inches, 3 inches and 4 inches diameter. Pressure tabs will be located for every 4ft in order to determine the pressure drop due to friction properly. Data will be collected from each pipe, and will be analyzed. After data collection from pipe viscometer, a sample will be taken from the sample tab just before the annular section to observe the physical properties of foam. After taking the sample, pressure drop due to friction will be observed in annular section.

In the ABM Meeting, May -1999, the first thoughts about the foam flow loop was presented. Initially, a re-cycling foam flow process was planned to be developed. The proposed method requires breaking the foam with decreasing its pH below a certain level, then reforming the foam by increasing the pH again to its original level. This way, it would be possible to use the same foaming solution continuously with some minor addition of foaming agent into the solution. Preliminary laboratory testing of a commercially available system from ECD-Clearwater Company have shown that efficiency of re-generating the foam using pH-adjustable system is not very high. The proposed plan was also discussed at the ABM with industry members. Taking into account criticisms and comments made, it was decided not to use pH-controllable system. This required, however, modification on the design of the experimental facility. A schematic of the modified experimental facility is shown in Figure-1. Major differences between the system introduced in May-1999 ABM meeting and the new one are as follows;

1. No pH adjustment is required in the new system, so there will be no need for any acid or base injection. There will be a need for , however, a continuous addition of foaming agent into the system.
2. Initially, it was thought that a separator was required in order to separate the gas and the liquid part after breaking the foam. In the new system, separator is not required. The foam will be broken by spraying stream of water onto the foam when it is discharged on the shale shaker. Foam breaking process will be enhanced by forcing diluted foam solution to pass through a foam breaker film, which is present in the collection tank. Spraying water onto foam will also help the cuttings separation from foam .

5.3.1 Elements of the Modified Experimental facility

Foaming agent and water will be mixed in the generation tank. If more solution is required, it will be supplied from the spare tank. The mixture will be pumped to the system using a centrifugal pump. Air will also be sent to the system by the help of the compressor with a capacity of 1400 SCF at 120 psi discharge pressure. The rates of liquid and air will be measured by using mass flow meters. Then, liquid and air will be mixed by using a static mixer in order to create foam. Foam will directly enter to the pipe viscometer (Figure-2). The pressure at the entrance of the pressure transmitter will be measured by using a gage pressure transmitter. The differential pressure drop through each pressure tabs will be measured by using a differential pressure transducer. The dashed line in Figure-1 represents the differential pressure transducer line for pipe viscometer, and the solid line represents the differential pressure transducer line for the annular section. After collecting data from the pipe viscometer, foam will enter though the annular section. At this part, cuttings will also be added into the solution. Foam will go to the shale shaker after flowing through the annular section. At the top of the shale shaker, a shower system is installed (Figure-3). There are 16 adjustable nozzles present. The system is connected to a water line of 70 gal/min capacity, and 12 of these nozzles are also connected to a pumping system that

has a pumping capacity of 100 gal/min from the bottom of the collection tank. Cuttings and foam are separated here. The shower system will force foam pass through the shale shaker and a film of foam breaker that is present in the collection tank. Once the foam is passed through this film, the foaming agent cannot trap gas bubbles anymore, so the foam is broken. The small scale foam flow loop experiments have shown that, it is not possible to re-generate foam from the solution that is passed through the foam breaker once.

5.3.2 Flow-Loop Modification/Construction

The modification of the TUDRP/LPAT loop for foam flow is completed. The flow-loop is now ready for pressure tests and calibration runs with water, air, and water + air.

- The preparation of supports for the acrylic pipes and the static mixer are finished. The couplings installation for joining the acrylic pipes are done. Pressure tabs are also located. The joints of pipe viscometer to the flow loop are also constructed and installed on the flow-loop.
- The shower system is constructed. It is made up of PVC pipes, control valves and adjustable nozzles (Figure-3). The pump installation is finished and connected to the water line.
- Gauge pressure transmitter is installed in front of the pipe viscometer.
- Check valve for low liquid flow rates is installed to the loop.
- The spare tank and the generation tank installations are finished. The pipe connections of the tanks are also done.
- Modification of the data acquisition system for cuttings transport has been recently completed.

5.4 EXPERIMENTAL PROGRAM

After finishing the water, air, and water + air runs and calibrations, preliminary experiments for foam rheology will be performed. The rheology experiments will be conducted for qualities varying from 40% to 95% with velocities in the annular part from 0.5 ft/sec to 2.5 ft/sec. The schedule of the experiments for 2 weeks period is given in Table-1. After finishing the rheology experiments, cuttings transport part will begin.

5.4.1 Properties of the Foaming Agent and the Foam Breaker

The foaming agent and foam breaker that will be used for the experiments will be supplied from “Bachman Drilling & Production Specialties, Inc.”. The technical data for the chemicals are as follows;

Foaming Agent : DrillFoam FF-4000

This product is a solution of anionic foaming agents and foam boosters developed for use in stable foam drilling operations. It is soluble in fresh water and brine. FF-4000 has a density of 8.51 ppg, a flash point of 125°F, a pour point of -30°F, and the pH level for 10% solution is 8.5-9.0. The recommended concentrations are ranging from 0.75% to 2%. This product is biodegradable when diluted in fresh water.

Foam Breaker : FoamBreak DF-104

This product is a high molecular weight alcohol based defoamer designed for foam drilling operations. DF-104 effectively breaks the bubble structure of both polyhedron and sphere foams, allowing the trapped gas to be released from the fluid. Foam breaker is insoluble in water and brine. DF-104 has a density of 7.5 ppg, a flash point of 85°F, a pour point of -40°F.

5.5 COMPUTER PROGRAM

A computer simulator is being prepared for determination of frictional pressure losses of foam flow in horizontal pipes. Finite difference technique is used along a specified pipe segment. The pipe is divided into grids, so, pressure loss, quality, density, etc. is determined in every grid. Calculations are based on six different hydraulic models^{6, 7, 8, 11, 15, 19}.

After finishing the development of the source file for all models, comparison among the models will be done. For further plan, annular section will be added to the simulator. Also, inclined section will be added. Finally, cuttings transport part will be included, and proposed model in this study will be compared to the previous models.

5.6 REMARKS AND CONCLUSIONS

There are several research done about the rheology of foam, however, only a few studies are present about cuttings transport with foam. No literature is found on cuttings transport with foam in inclined and horizontal wells.

There are two main approaches to define the foam properties;

- i) Quality based approach
- ii) "Volume Expansion Ratio" based approach.

In the first approach, the change in quality is determined along the pipe, and rheological properties are evaluated for each change in quality. Therefore, determination of pressure losses due to friction is difficult.

In the second approach, shear stress-shear rate values are normalized by using "volume expansion ratio". Shear stress vs. shear rate plots for different qualities seems to be on the same curve, independent of pipe geometry. This approach assumes a "constant friction factor" along the pipe, so if inlet properties of the foam are known, it is possible to determine the frictional pressure losses at any point in the pipe by using the same rheological model parameters at the inlet.

NOMENCLATURE

β	Slip coefficient
μ_o, μ_p	Plastic viscosity
τ_o, τ_y	Yield point
D	Pipe diameter
ρ	Density

g_c	Gravitational constant
K	Consistency index
L	Pipe length
m	Mass
M	Molecular weight
n	Flow behavior index
P	Pressure
Q	Flow rate
Γ	Quality
R	Gas constant
γ	Shear rate
τ	Shear stress
ε	Specific volume expansion ratio
T	Temperature
V	Volume
v, u	Velocity
μ	Viscosity
w	Mass fraction
Z	Compressibility

Subscripts

L, l	Liquid
G, g	Gas
s	Solid
F, f	Foam

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Figure-1 LPAT Flow Loop Modification for Foam Flow

Figure-2 Pipe Viscometer

Figure-3 Shower System for Breaking the Foam

Table-1 10 Days Experimental Program

<u>Week-1</u>			<u>Week-2</u>		
Day-1			Day-1		
<i>Exp.-1</i>	Quality	90%	<i>Exp.-1</i>	quality	80%
	velocity (annular) (ft/sec)	0.5		velocity (annular) (ft/sec)	1.5
<i>Exp.-2</i>	Quality	90%	<i>Exp.-2</i>	quality	80%
	velocity (annular) (ft/sec)	1		velocity (annular) (ft/sec)	2
Day-2			Day-2		
<i>Exp.-1</i>	Quality	90%	<i>Exp.-1</i>	quality	80%
	velocity (annular) (ft/sec)	0.5		velocity (annular) (ft/sec)	2.5
<i>Exp.-2</i>	Quality	90%	<i>Exp.-2</i>	quality	80%
	velocity (annular) (ft/sec)	1		velocity (annular) (ft/sec)	0.5
Day-3			Day-3		
<i>Exp.-1</i>	Quality	90%	<i>Exp.-1</i>	quality	95%
	velocity (annular) (ft/sec)	1.5		velocity (annular) (ft/sec)	0.5
<i>Exp.-2</i>	Quality	90%	<i>Exp.-2</i>	quality	95%
	velocity (annular) (ft/sec)	2		velocity (annular) (ft/sec)	1
Day-4			Day-4		
<i>Exp.-1</i>	Quality	90%	<i>Exp.-1</i>	quality	95%
	velocity (annular) (ft/sec)	2.5		velocity (annular) (ft/sec)	1.5
<i>Exp.-2</i>	Quality	80%	<i>Exp.-2</i>	quality	95%
	velocity (annular) (ft/sec)	0.5		velocity (annular) (ft/sec)	2
Day-5			Day-5		
<i>Exp.-1</i>	Quality	80%	<i>Exp.-1</i>	quality	95%
	velocity (annular) (ft/sec)	1		velocity (annular) (ft/sec)	2.5
<i>Exp.-2</i>	Quality	80%	<i>Exp.-2</i>	quality	95%
	velocity (annular) (ft/sec)	1		velocity (annular) (ft/sec)	1

6. STUDY OF CUTTINGS TRANSPORT WITH AERATED MUDS UNDER LPAT CONDITIONS

This study has been initiated in January 1999. The project proposal has been prepared and presented at the May 1999 Advisory Board Meeting of ACTF-JIP. The proposal was well received by ACTF and TUDRP member companies. The following section presents the proposal and the progress made in this project since January 1999.

Project Title: Determination Of Minimum Water-Air Flow Rate Required For Effective Cuttings Transport In High Angle And Horizontal Wells

Investigator: Paco Vieira

Objectives:

1. Determine experimentally the minimum flow rates for water and air that guarantee the hole cleaning while drilling horizontal and near horizontal sections.
2. Develop several charts that help the user determine minimum requirements of air and water injection rates to plan high angles and horizontal sections, using air-water system as drilling fluid.

6.1 INTRODUCTION

One of the primary functions of a drilling fluid is to transport efficiently the drilled particles (cuttings) to the surface through the wellbore annulus. This property is called the “carrying capacity “ of drilling mud. During the past 2 decades, especially in recent years, many studies have been conducted to obtain a better understanding of the cuttings transport phenomena. Several mechanistic models and empirical correlations have been developed in order to give the drilling engineer better tools that help him to design efficient hydraulic programs and assure the economical success of drilling a hole. As is well know, improper hole cleaning could create problems such as stuck pipe and increased in torque and drag that cost to the oil industry millions of dollars in losses.

In deviated and horizontal well drilling, the drill cuttings tend to fall to the lower side of the hole because of the gravity effect. The continuous accumulation of cuttings in the lower side of the wellbore creates a “Cuttings bed” when improper hydraulic conditions are used (Fig. 1). Since deviated and horizontal well drilling become more common it is necessary to create better understanding of the cuttings transport phenomena for these applications. There is a definite need of better understanding of all the parameters that affect the formation of a cutting bed in deviated and horizontal sections and operational procedures to avoid this undesirable situation. Application of horizontal and deviated well drilling it has been combined in recent years with the non-conventional drilling techniques

Under balanced and near balanced drilling. In Underbalanced / Near-balanced drilling mixture of liquid and gas are commonly used as a drilling fluid to reach the desired differential pressure condition. Examples of these fluids are aerated mud, foam and mist. The increased use of non-conventional fluids in horizontal and deviated well drilling created a need of understanding cuttings transport under these conditions. As part of these recent efforts, this research is dedicated to investigate cuttings transport in horizontal and near-horizontal wellbores by using an aerated mud system.

Fig 1- Bed of cuttings in directional and horizontal drilling

6.2 STATEMENT OF PROBLEM

Cutting transport has been studied for horizontal and vertical wellbore configuration using conventional drilling fluid systems (single phase). Experiments have been conducted by many investigators to determine the minimum flow rates needed to avoid problems that are created by insufficient cleaning, however there is a big lack of information when two-phase fluids are used for drilling purpose. The increasing use of aerated drilling fluids, foam and mist, in high angle wellbore, has created the need of understanding cuttings transport in those conditions. Also for production purposes (after drilling) two phase flow is commonly used in the oil industry to clean sand production that is accumulated in the well and affecting the production rate. It is a normal procedure in this case to run a Coiled-tubing unit and circulate the sand with gasified liquid at high rates but there is no knowledge about the optimum flow rates that could be used in order to reduce operations costs.

In order to understand the mechanism of cutting transport using multiphase fluids experiment will be conducted using the TUDRP- Low Pressure ambient temperature flow loop.

In order to obtain a complete operational domain of the low-pressure ambient temperature flow loop, previous experiments a three step experimental program have been adopted. As a first step experiments using single phase (Water) were conducted. The second step experiments using two-phase flow (Water/Air) were conducted. Finally three phase (Air/Water/Cutting) have been scheduled and some preliminary test have been conducted.

6.3 SCOPE

The scope of this study is to investigate the effect that the variables presented in Table 1 have on cutting transport:

INDEPENDENT VARIABLES	DEPENDENT VARIABLE
Air flow rates	Equivalent mud weight.
Water flow rates.	Pressure drop.
Hole inclination	Flow patterns

Table 1- Variables

The following preliminary test matrix is proposed:

CFM	0	250	500	750	1000	1250	
GPM	150	200	250	300	350	400	450
Inc. (°)	90	80	70	60	50		
ROP (ft/h)	10	20	30				

Table 2- Test Matrix proposal

Volumetric flow rate of gas at field condition is given by the real gas law as:

$$Q_{gasfc} = Q_{gaslc} * \frac{P_{lc}}{P_{fc}} * \frac{T_{fc}}{T_{lc}}$$

Cuttings injection rate is given by:

$$C_{in}(lb/min) = ROP(ft/h) * A_h(ft^2) * C_{den}(lb/ft^3) / 60(min/h)$$

6.4 LITERATURE REVIEW

Cutting Transport

Larsen (1990) [1], conducted several experiments using a low pressure, low temperature, flow loop at TUDRP to study the effect of inclination, annular flow, mud rheology, drill pipe eccentricity, cutting size, mud weight, drilling rate, and drill pipe rotation on the critical fluid velocity needed to avoid cutting bed formation. He developed empirical correlations to predict bed height and critical cuttings transport velocity. In the experiments Larsen could observe that in angles between 40° and 90° the flow requirements were strongly dependent of the angle of inclination, whereas for high angles the eccentricity has no significant effects on the critical velocity for cuttings transport. Also he could determine that smaller cutting particles are more difficult to clean and the annular critical transport velocity increases with the rate of penetration.

In 1993, Jalurkar [2] studied the effect of hole size on the critical and sub-critical velocities. The objective of this study was to develop empirical correlations to introduce hole geometry into the Larsen's model. The most important conclusion

was that for subcritical flow, the effect of hole size on cuttings bed was insignificant.

In 1997, Sanchez [3] presented his results on the effect of pipe rotation has a significant effect on the hole cleaning during directional well drilling. The study show that the cuttings concentration is a function of rotary speed, hole inclination and flow rates.

In 1997, Azar and Alfredo Sanchez [4], presented a paper for a SPE drilling conference where they defined the factors that influence hole cleaning as annular fluid velocity, drill string rotation, mud properties, drilled cuttings, annular eccentricity and drilling rate. They also discuss their limitation in actual field practices.

In 1999, J. Li [5] presented the result of his study on experimental analysis of cuttings transport in a multi-phase system (gas-liquid-cuttings). He investigated effects of the liquid/gas volume flow rate, in-situ liquid velocity, ROP, inclination angle and fluid properties on the cuttings bed height. He observed that the fraction of the circulation liquid has a significant impact on the cuttings transport. He also observed that the changing of liquid flow rate has more effect on the cuttings transport than the gas volume flow rate.

In 1996 Ali Pilehvari [6] presented the State-Of-Art in Cuttings transport in Horizontal Wells. He summarized the results from pioneering experimental work done in cuttings transport the remarking of the pioneer experimental works done in cuttings transport using TUDRP test facility at the University of Tulsa. These works has been done in a flow loop that is capable to vary and control inclination angle, mud pumping rate, drilling rate, drill pipe rotation and eccentricity. Test conducted in this facilities show that is a significant difference between the cutting transport in inclined wellbores and that of vertical. It was seen that the mud rheology and flow regimes have a considerable impact on cuttings transport. However, the effects were different for horizontal and vertical wellbores. The paper also discusses the models that have been developed in recent years for cuttings transport and the future research and technology needs.

In 1990 Peden, Ford and. Oyeneyn [7] presented results of an experimental study of the influence of hole inclination angle, cuttings size, drill-pipe eccentricity, flow rate, annular geometry and pipe rotation on the minimum cuttings transport velocity. They observed that the hole inclination angle has a strong effect on cuttings transport. They found that the worst situation occurs in angles between 40 and 60 degrees. They also observed that smaller cuttings are transported more efficiently at all inclination angles using low viscosity fluids while in angles between 0 and 50° largest cuttings are transported efficiently. The cuttings transport for this case is strongly influence on flow pattern. Eccentric annuli is easier to clean than concentric one. In large annuli, pipe rotation has no significant effect on hole cleaning.

In 1996 A. L. Martins [8], presented an experimental study of the erosion of a cuttings bed deposited at the bottom of a horizontal section using Newtonian fluids. In his study he evaluated the effect of hole and drill pipe diameter, eccentricity, inclination, cuttings diameter and drill pipe rotation on the cutting bed removal. Based on the result empirical correlation were developed.

In 1992, Guoqiu Fang [9] presented results of an experimental study of the free settling of cuttings in Newtonian and non-Newtonian fluids. Two settling patterns of cuttings were observed as stable and swinging. New predictive expressions for the drag coefficient of cuttings and for the settling velocity of cuttings were also developed for the two settling patterns.

In 1993, Guo, Hareland, and Rajtar [10], presented a theoretical model to predict the required air and mud flow rates in aerated mud drilling operation, based on the carrying cutting capacity and the maximum rate of penetration for vertical holes. In this approach they treated the multiphase fluid as a homogeneous mixture of liquid, gas and solid flowing in a bubbly flow regimen. They defined the carrying capacity of the aerated mud as the maximum cuttings that can be lifted by it. They calculated the terminal slip velocity using Rittenger's equation for vertical flat particles, where they assumed drag coefficient as 0.94.

$$V_{sl} = 7.3 \sqrt{\frac{D_c(\rho_c - \rho_f)}{\rho_f}}$$

They defined the required cuttings transport velocity as follow:

$$V_t = \frac{ROP}{C_c}$$

Where they consider the maximum cuttings concentration (C_c) admissible as 4% by volume.

In 1995 Campos [11] presented two mechanistical models for predicting, cuttings transport in highly incline wellbore. The first model, one dimensional mechanistical model, takes into account only the area average, fluid velocity and cuttings concentration across an annular section. The second, a solid liquid model, take into account the fluid velocity and cuttings concentration profiles. Model prediction are compared to experimental data obtained from different flow loops. The results show that the first model is sufficiently accurate for practical application. Improvements however, would be archive by including the effect of liquid and solid velocity profiles and cuttings concentration distribution in the annulus across the section. The results of the second model indicated that prediction of flow rate and rate of penetration, that are required for maintaining the solids suspended, show good agreement with the experimental data.

In 1993 Iyoho and Takahashi H [12] presented a new mathematical models for solid-liquid flow at low throughput velocities for different configurations of horizontal and eccentric annuli. At velocities below the deposition velocity, flow characteristics include the formation of dunes, coupled with velocity and pressure fluctuations. This quasi-steady flow occurs frequently in highly deviated well bores. Slurry dunes observed from laboratory experiments are modeled as continuous triangular waves. The Bernoulli and the continuity equations are used to develop mathematical relations linking the annulus conduit dimensions, velocity, pressure, and concentrations. Preliminary model tests with laboratory pipe data from previous studies show reasonable agreement. They also presented an extensive review on the basic relationship and differences between pipeline and annular slurry flow in vertical and horizontal flow.

In 1995 Bassal [13], investigated the effect of drill pipe rotation on hole cleaning during directional well drilling. A 8-in. diameter well-bore simulator, 100 ft long, with a 4-in. drill pipe is used for the study. Variables considered in this experimental work are drill pipe rotary speed, hole inclination, mud rheology, cuttings size, and mud flow rate. A total of 576 tests were conducted. Results have shown that drill pipe rotation has a significant effect on hole cleaning in directional well drilling. The level of enhancement in cuttings removal as a result of drill pipe rotary speed is a function of the combination of mud rheology, cuttings size, mud flow rate and the manner the drill string dynamically behaves. Generally, smaller cuttings are more difficult to transport. However, using high rotary speed with high viscosity mud, small cuttings become easier to transport. Low viscosity mud in the hole cleans better than high viscosity mud with no drill pipe rotation.

6.5 TWO PHASE FLOW - FLOW PATTERNS IDENTIFICATION

The two phase flow is characterized by a large number of flow variables. The two phase flow (Gas-Liquid) the liquid and the gas can be distributed in the pipe in a variety of flow configurations. The flow configuration differs from each other in the special distribution of the interface. The distribution of the interface it is mainly governed by gas and liquid volumetric fractions. The flow patterns depends mainly on the liquid and gas volumetric fraction. In 1982 Shoham define an acceptable set of flow patterns based in experimental data acquired from vertical and horizontal well flow experiments [14].

– Flow Patterns in Horizontal Flow

Stratified Flow:

Occurs at relative low gas and liquid flow rates. This configuration can be also classified in two "Stratified Smooth" and "Stratified Wavy" (Fig 2).

Fig 2- Flow Pattern- Stratified Flow

Intermittent Flow:

Alternate of liquid and gas flow characterizes intermittent flow. Can be also classified in two groups as "Elongated Bubble" and "Slug" (Fig. 3).

Fig 3- Flow Pattern for horizontal flow - Intermittent

Annular Flow:

Annular flow occurs at very high gas flow rates. This configuration can be also classified in two groups as "Annular" and "Wavy Annular" (Fig 4).

Fig 4- Flow Pattern for horizontal flow - Annular

Dispersed Bubble Flow:

Dispersed Bubble flow occurs at a very high liquid flow rate (Fig.5).

Fig 5- Flow Pattern for horizontal flow- Dispersed Bubble.

– Flow Patterns Vertical Flow

Bubble Flow:

Bubble flow occurs for low gas flow rates. (Fig. 6)

Fig 6- Flow Pattern for vertical flow - Bubble Flow

Slug Flow:

In this flow pattern most of the gas phase is located in a large bubble called "Taylor Bubble" with diameter almost equal to the pipe diameter. The flow consists of successive Taylor bubbles. (Fig 7).

Fig 7- Flow Pattern for vertical flow - Slug Flow

Churn Flow:

An oscillation motion characterizes this flow pattern. Churn flow is similar to slug flow but looks more chaotic. (Fig. 8)

Fig 8- Flow Pattern for vertical flow - Churn Flow

Annular Flow:

In the annular vertical flow the liquid phase moves slower as a film around the pipe wall (Fig. 9).

Fig 9- Flow Pattern for vertical flow - Annular Flow

6.6 SINGLE PHASE FLOW EXPERIMENTS

For the single-phase experiments the following test matrix was used:

1. Inclination angle: 90°
2. Drill pipe rotation: 0
3. Liquid flow rates:

GPM	50	100	150	200	250	300	350	400	450	500	550
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Table 1- Liquid flow rates range for single-phase experiments

Experimental pressure drop measurements were compared with the model results obtained from the following formula:

$$\frac{dP}{dL} = \frac{\rho^{0.75} * v^{1.75} * \mu^{0.25}}{1396 * (d_2 - d_1)^{1.25}}$$

Fig 10- Single Phase- Pressure Drop (Theoretical and Experimental)

The difference between experimental and theoretical pressure drop values was found to be around 8%.

6.7 TWO-PHASE FLOW EXPERIMENTS

The experiments were conducted for the horizontal position without drill pipe rotation using the range of liquid and air flow rate as shown in Table 2.

Table 2. Two-Phase experiments – Test Matrix

Liquid Flow	Gas Flow
Rate GPM	Rate SCFM
100	30
100	45
100	60
100	75

Average total pressure drop, liquid hold up and flow pattern identification is presented in Table 3.

Table 3- Result of Two-Phase Flow experiments

Liquid Flow	Gas Flow	Vsl	Vsg	Pressure Drop	Flow Pattern
Rate GPM	Rate SCFM	(ft/s)	(ft/s)	Psi	
100	30	0.93370603	2.09538854	0.16	Elongated Bubbles
100	45	0.93370603	3.14308281	0.21	Elongated Bubbles
100	60	0.93370603	4.19077708	0.28	Slug
100	75	0.93370603	5.23847135	0.29	Slug

Pressures drop was measured using differential pressure transducers over a distance of 76.05 ft.

Previous investigator have done two phase flow experiments in the TUDRP-LPAT flow loop, using similar flow rates of gas and liquid and identifying the same flow patterns that have been observed in this test.

NOMENCLATURE

Q_{gasfc} = Gas flow rate at field conditions (scfm)

Q_{gaslc} = Gas flow rate at loop conditions (scfm)

P_{fc} = Pressure at field conditions (psi)

P_{lc} = Pressure at loop conditions (psi)

T_{fc} = Temperature at field condition (°F)

T_{lc} = Temperature at loop condition (°F)

ρ = Density (lb/gal)

v = Fluid Velocity (ft/s)

μ = Viscosity (cP)

d_2 = Hole diameter (in)

d1 = Drill pipe Outside Diameter (in)

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7. STUDY OF FOAM FLOW BEHAVIOR UNDER ELEVATED PRESSURE AND ELEVATED TEMPERATURE CONDITIONS

This study has been initiated in September 1999. A new project proposal has been prepared and will be presented at the ACTS-JIP Advisory Board Meeting to be held on November 11, 1999.

Project Title: Study of Foam Flow Under Simulated Downhole Conditions

RESEARCHER: Affonso Marcelo Fernandes Lourenco

Chemical Engineer graduated in 1997 from Federal Fluminense University, Rio de Janeiro, Brazil. Worked at CENPES – PETROBRAS RESEARCH CENTER from 1995 to 1999 as a researcher. Joined the TUDRP/ACTF team in August 1999.

OBJECTIVES

- Perform experimental study of foam flow behavior inside pipes and annulus in large-scaled loop under elevated pressure and temperature.
- Development of empirical correlation to estimate pressure losses during foam flow under given gas-liquid ratio, temperature and pressure conditions.

SCOPE

- Conduct a extended review of the related literature on this complex type of flow.
- Modify ACTF flow loop for foam flow under elevated pressure and temperature, aiming optimum flow conditions to the experiments.
- Develop methodology for foam bubble characterization.
- Conduct experiments to measure pressure losses during foam flow as a function of pressure, temperature and foam quality (liquid and gas rates).
- Develop empirical correlations to determine pressure losses as a function of pressure, temperature and foam quality.

DELIVERABLES

- Advisory Board Meeting Progress Reports and Final Report.
- Experimental Data on Foam Flow Behavior.
- Empirical Correlations to determine pressure losses as a function of pressure, temperature and foam quality.

EXPECTED COMPLETION DATE

Fall of 2001

7.1 INTRODUCTION

The use of lightweight fluids in drilling operations is becoming common practice all over the world. Lightweight drilling fluids have several advantages when properly applied. Energized fluids are normally used in old and depleted zones to enhance productivity or to overcome operational difficulties such as drilling in large fractured formations. The applicability of drilling with lightweight fluids goes further in nowadays. Benefits as the reduction of drilling time due to increased rate of penetration, low costs of stimulation operations due to minor formation damages and producing while drilling when trespassing pay zones in under-balanced or near balanced conditions, justify the interest in the use of lightweight fluids.

Among the numerous types of lightweight fluids used in drilling operation, foam appears to be a widely used technique. This is mainly because of the fact that foam generates very low ECD and formation damage, while exhibiting high hole cleaning capacity. Cost often requires the drilling of high angle well with complex trajectories. In order to achieve success in drilling operations under this scenario, the understanding and design of hydraulics properties of this compressible fluid becomes a major issue.

Foam flow behavior have been studied by several researches in the past. However, there is no general agreement among them on the rheological description of the foam. The analysis of foam flow behavior is rather difficult because of the number of variables involved such as: compressibility of the fluid, type and size and geometry of the facility, method of foam generation, liquid and gas phase types, etc. Considering the complexity of the flow, sometimes effects as slip at the wall, texture of the foam and shear rate range are neglected. In addition, the effects of elevated pressure and temperature in a large-scale flow facility were not studied at all. This study therefore, will focus on the effects of some of the less known variables such as temperature and pressure and therefore flow behavior.

7.2 PRELIMINARY LITERATURE REVIEW

In this section, a summary of the past experimental work on the foam flow behavior will be given. This preliminary review is extended to the works related to the effects of pressure and temperature on the foam flow behavior. There are many issues related to foam flow still not well understood. A lot of controversy and different approaches and assumptions are present when trying to model foam flow. The presence of yield stress, effects of slippage at the solid surfaces, the foam generation and its influence on texture, the type of liquid and gas phase and their influence on rheological properties, the effect of temperature and pressure on these variables are some of the items still under discussion.

Heller and Kuntamukkula¹ in a critical literature review of foam rheology, stated difficulties encountered in foam rheology measurements. Since foam is a heterogeneous dispersion of gas in a liquid phase, the first difficulty arise from the statistical variation of measurements as individual cells passed by pressure measuring ports in tube viscometer. Further complications are due to

modification of shear distribution within the flow channel, time dependency and compressible characteristics.

David and Mardsen² working with aqueous foams in a pipe viscometer concluded that it behaves like a shear thinning fluid with very low gel strength. Dependence on pipe diameter of the rheological parameters was detected. The slippage at the wall was observed and corrected using Mooney's method. They concluded that the slip increases with shear stress and wet foams. After slip correction, they found that apparent viscosity did not change with quality.

Beyer, Millhone and Foote³ formulated equations for steady-state flow of aqueous foam in circular pipes using results of bench-scale and pilot scale pipe flow experiments. Based on data of pressure drop and lifting force of foam flowing past a 3/16 in. diameter sphere, they concluded that velocity and liquid volume fraction (ratio between volume of liquid and volume of foam) were the two important independent variables governing flow behavior and particle lifting ability of foam. These results matches with Mitchell⁴ results. They considered foam as Bingham fluid and slip at the wall was detected. Working in a range of 0 to 860 psig of pressure and 70 to 180 °F of temperature, they observed that the increment on pressure increased shear stress. On the other hand, an increase in temperature decreases shear stress for a specific liquid volume fraction and velocity. Besides that they developed a model to predict pressure losses during foam flow through vertical annulus by considering the Bingham velocity profiles into narrow slit. Comparison of the results of proposed model with field data, revealed that results are influenced by the pipe diameter.

Reidenbach and Harris⁵ (1983) used a pipe viscometer to investigate flow behavior of foams formed by nitrogen and carbon dioxide. They found that rheological parameters were dependent of the type of liquid phase and quality. In laminar flow, pure water based foams could be characterized as a Bingham plastic fluid. Otherwise gelled water foams had pseudo-plastic behavior with a yield point. Foams with qualities below 60% demonstrated linear dependence with quality for yield point (eq. 1). An exponential function was proposed for the yield point of high quality foams (eq.2). The consistency index demonstrated to be dependent of liquid phase consistency index and quality as shown (eq.3).

$$\tau_{yp} = C_1 \Gamma$$

(1)

$$\tau_{yp} = C_2 e^{C_3 \Gamma}$$

(2)

$$K_f = K_L e^{C_1 \Gamma + C_2 \Gamma}$$

(3)

τ_{yp} - yield point

K_f – consistency index of foam

K_L – consistency index of liquid

The turbulent flow regions was also investigated and the following equation proposed to represent the flow (eq.4):

$$\tau_w = A \rho^x D^e \left(\frac{8v}{D} \right)^s$$

(4)

τ_w - Wall Shear Stress

A – parameter that incorporates the effects of fluid viscosity and density in turbulent flow

x – correction factor for parameter A for compressible fluids

ρ - density of foam

D – Diameter of the pipe

e – correction factor for diameter effect

v – velocity

s – indicative parameter of turbulence and non-Newtonian behavior

These constants were evaluated by plotting the graph of wall shear stress, τ_w versus shear rate ($8v/D$) in the turbulent region.

Reidenbach and Harris⁶ (1987) investigating the effects of high temperatures (up to 300 °F) foam rheology on similar pilot scale loop, came up with corrections for consistency index K and flow behavior index n . Based on the previous results developed at 75°F and considering the yield point as a function only of quality, the follow equations were proposed:

$$n_t = n_{75} e^{(0.0028 - 0.0019 \Gamma)(T - 75)}$$

(5)

$$k_t = K_{75} e^{(C_2 \Gamma - 0.018)(T - 75)}$$

(6)

where C_2 is defined :

$$C_2 = e^{-(3.1\Gamma + 3n_{75})}$$

(7)

Analyzing experimental results, they found that the viscosity increases with quality and gelling-agent concentration. Temperature thinning effect was greater at low quality. The increase in flow behavior index due to the increase in the temperature was also high at low quality. Consistency index seemed to be decreasing more with the increase of temperature at low quality foams.

Cawiezel and Niles⁷ studied the behavior of water and gelled based nitrogen foams under high pressure, temperature and shear rates in a lab-scale facility. He investigated bubble size distribution and suggested that the existence of yield point as well as its behavior is a function of foam structure. According to the authors, the development of the yield point above 52% quality (initial gas fraction where the fluid is considered foam) could be explained by the appearance of cubic packing "foam structure". Below this quality the sphere bubbles would not interfere with each other. At 74% quality the packing arrangement would be hexagonal which would cause large increase in viscosity and yield point. Above this quality spherical bubbles would undergo shape distortion and packing would become polyhedron, resulting greater increase in foam viscosity. Pressure up to 10000 psi were simulated and results showed, for

water being the liquid phase, that the texture or bubble size distribution was affected when pressure increased. The apparent viscosity of 55% foam quality increased with pressure increase due to reduction of bubble size. The opposite effect on apparent viscosity was found for 70% quality foam. Apparent viscosity was found to be decreasing as temperature increase up to a critical value of 150°F. Above this temperature, no significant reduction at the apparent viscosity was observed. The behavior of the gelled water based foams was similar to the pure water based foams.

Harris⁸ (1995) performed an experimental study using a flow-loop viscometer. He used nitrogen and carbon dioxide mixed foams, based on corboxymethylhydroxypropylguar, with fixed 70% quality and found out that the stability of the system is high when increasing carbon dioxide percentage. Additional results revealed yield point of CO₂ foams was three times greater than N₂ foams. In the same study, he also observed that rheological properties of the mixed nitrogen-carbon dioxide foam were very similar to pure nitrogen and carbon dioxide foams.

Saintpere, Herzhaft and Toure⁹ performed tests with aqueous foam in a parallel plates rheometer under ambient conditions. They concluded that rheological properties combine elastic, viscous and yielding phenomena. The slip effect was detected and avoided using grooved surface plates on tests. Remarks on the transitory regimes evaluation was given and data were built in average shear rates where stability and inertial effects could be avoided.

Valko and Economides¹⁰ introduced an interesting approach to model the foam flow. This is called volume equalization method and it is based on the definition of specific expansion ratio (eq.8):

$$\varepsilon_s = \frac{\rho_l}{\rho} \quad (8)$$

It was shown that the use of specific expansion ration concept, enables to construct just one major flow curve for different qualities and pressures. Using the basic definition of specific expansion ratio, the volume equalized Power Law (eq.9) and Bingham (eq.10) constitutive equations can be written as follows:

$$\tau = (K \varepsilon_s^{1-n} |\gamma|^{n-1}) \gamma \quad (9)$$

$$\tau = \left(\frac{\tau_y \varepsilon}{|\gamma|} \right)^s + \eta_p \gamma \quad (10)$$

for

$$\tau > \tau_y \varepsilon_s \quad \text{and} \quad \gamma = 0 \quad \text{for} \quad \tau \leq \tau_y \varepsilon_s$$

Where the rheological parameters K, n, η_p and τ_y are constant for the foams at a given gas-liquid pair at given temperature. The advantage found in the new approach was the constant friction factor along the pipe for an isothermal foam flow, allowing simple evaluation of pressure loss due to friction. All experiments were carried out on a high pressure (up to 2MPa) and low temperature (up to

22°C) large-scale loop. The data were valid for low expansion foam, $\varepsilon_s < 4$, characterized with spherical bubbles.

Winkler¹¹ in his study of foam rheology in circular pipes with different concentrations of polymer (HPG) as liquid phase, varying quality from 30 to 75%, circulating pressures up to 430 psi and temperatures up to 40°C, found good agreement with the experimental data using the volume equalized power law constitutive equation. He confirmed the invariable principle of the friction factor for a given mass flow rate and isothermal foam flow as well as invariance of the volume equalized power law model with geometry. The temperature seemed to have no influence on fluid behavior index and confirmed Reidenbach and Harris⁴ observations that temperature thinning effects are greater at low quality foams.

Gardiner, Dlugogorski and Jameson¹² examined rheological properties of fire-fighting foams and confirmed the applicability of volume equalization model to more expanded foams, $\varepsilon_s > 5$. The slippage at the wall was observed and corrected using the method of Oldroyd-Jastrzebski. Unlike previous investigation they observed that the correct slip coefficient decreases with wall stress.

7.3 ADVANCED CUTTINGS TRANSPORT FACILITY

The experimental work will be carried out by using Advanced Cuttings Transport Facility flow loop. Flow loop has three different pipe diameters (2, 3, and 4 inch) and one 6 in. annular flow section. The 6 in. annular section contain a 3.5 in. inner pipe simulating wellbore annular geometry.

Currently, the facility is equipped with a high pressure mud pump with a flow rate capacity up to 300 GPM. Back-pressure valves allows simulation of 2000 psig pressures. Elevated temperature, up to 200°F, capability will be provided by using a parallel plates heat exchanger and a boiler. The instrumentation available now consists of a coriolis type flow meter, differential pressure and temperature transducers, control valves and relief pressure valves along the test section. All data can be monitored and stored by a data acquisition system controlled by LabView program.

Further developments of the flow loop will allow foam generation.

7.4 APPROACH

The approach will be initially experimental. Tests will be conducted to collect friction pressure loss data at different quality and flow rates under elevated pressures and temperatures. Data will be analyzed and empirical correlation or correction factors will be developed to incorporate the effect of elevated pressure and elevated temperature on foam rheological parameters and friction pressure losses.

- Experiments will be conducted to measure pressure losses at different foam quality (gas-liquid rates), pressure and temperature.
- Empirical correlations will be developed to estimate pressure losses during foam flow as a function of foam quality, pressure and temperature.

7.5 FUTURE WORK

Literature review will continue to understand the high pressure and high temperature effects on foam flow. Experiments will be conducted as soon as the flow loop is modified. Some preliminary work is also going to be conducted as the foam bubble characterization in close cooperation with instrumentation group of ACTS project. It will help to decide which effects should be considered, allowing set and optimize the test matrix as well as find the best approach for the problem.

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8. DEVELOPMENT OF CUTTINGS MONITORING METHODOLOGY

8.1 Objective:

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. These are:

1. Electrical
2. Optical
3. Ultrasound
4. X-Ray/ -Ray

8.2 Team Composition:

The instrumentation team charged with completing tasks 11 and 12 for the first year 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. In addition, Mr. Len Volk is a member of this team. Two MS level graduate students are assisting them. These students have BS degrees in EE and CS. This particular combination works well because successful completion of this project requires skills needed in both disciplines. To achieve 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.

8.3 Progress to Date:

The team started work on this project on August 15, 1999.

Since then we have developed an MS-Access database. This database will store information about all sensors that we identify. Using the database we can identify the appropriate sensors for each application. We have already searched the Internet to identify sensors and sensor manufacturers that should be included in the database. In the first stage of this process we have concentrated on sonic transducers. The database has the following fields:

- Product Name
- Company Name
- AddressLine1
- AddressLine2
- Zip
- E-mail
- Phone Number
- Web Address

- Sensor Frequency
- Beam angle
- Cost

A Visual Basic application has been designed and implemented to view the records. It allows the user to add new records and modify existing records. It also allows the user to query the database based on the values of beam angle, switching frequency and cost of the transducer.

Also, we have developed test plans for the first phase of task 11.

8.4 Approach:

In subtask one of the Task 11 we are to develop a static radial test cell and to develop a preliminary set of instruments to detect presence of cuttings in this cell. There are four different methods that can be used. These are:

- Ultrasound transmission
- X-ray/ γ -ray transmission
- Optical Attenuation
- Contrast in Conductivity and dielectric constant

Due to the fact that the pipes are going to be metallic the contrast in conductivity and dielectric constants are of very limited use. Therefore, we will not pursue them at this point.

The optical approach has potential in transparent fluids. Therefore, we will investigate this as a possible option if the other two approaches do not prove to be either economically or technically feasible.

X-ray/ γ -ray approach has good potential for success. However, there may be health risks associated with these so we will utilize them in a limited capacity unless ultrasound approach proves to be uneconomical or not feasible. Additionally, the cost of the X-ray/ γ -ray sensors appears to be prohibitively high.

Literature search revealed that Ultrasonic-transducers are more viable than X-ray transducers in the present context.

Ultrasonic sensors service the market by providing a cost effective sensing method with unique properties not possessed by other sensing technologies. Ultrasonic sensors are impervious to target material composition. The target material can be clear, solid, liquid, porous, soft, wood and any color. Dust, dirt or high-moisture environments do not affect ultrasonic sensors.

Ultrasonic sensors, which have low beam angle and high switching frequency, are needed for this project. There are a number of products currently available in the market, which satisfy the required criteria. Information pertaining to Ultrasonic-sensors manufactured by various companies has been collected and stored in a database (MS Access 97). This database is being continuously updated.

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 is possible to get an acceptable picture of what is inside the pipe. This is very similar to the ultrasound technique use by physicians.

8.5 Future Work:

To design and implement a test bed (a closed static system) to evaluate different designs of the ultrasonic sensing package. The sensors will be used to identify and monitor a known static concentration of cuttings in a simulated drill pipe.

In this stage we propose to build a cell consisting of two concentric pipes about 2 feet high. Cuttings of known size will be placed in a predetermined location in the cell (under a static environment). Using sensors we will try to locate these cuttings.

A PC based data acquisition system will be developed. This system will be used to store and process information received from sensors.

Glossary:

1. **Switching Frequency:** The maximum frequency at which the sensors is capable of turning on and off
2. **Beam Angle:** The beam cone angle values are the 3dB points (i.e., points at which the sensor signal is attenuated by at least 3dB). Outside this cone angle, the ultrasonic signal exists, but is rather weak.

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

9.1 Objectives

A method/apparatus is needed to measure the bubble size, distribution and shape during cuttings transport experiments. The challenge will be to photograph microscopic bubbles moving at a very high rate.

Subtask 12.1. Develop/Test a Microphotographic Method for Static Conditions. Under this Subtask, a method will be developed and an apparatus constructed for magnifying and recording static microscopic bubbles. The bubble images will be digitized and mathematically processed to obtain the bubble size, distribution and shape.

9.2 Project Status

Magnification. Bubble size in foams can vary over a wide range, depending on how the foam is prepared, the final system pressure and the chemical composition, but it is not uncommon to find bubbles with diameters down to 10 μ (0.01 mm). We will need a microscope capable of magnifying bubbles of this size so that they can be digitized and analyzed. As an example, one microscope at x45 power has a field of 3.30 mm. Based on examples of bubble images, if we assume that an image (microscope field) having the width of 35 bubbles can be satisfactorily digitally processed, then bubbles 0.01 mm diameter will require a field of 0.35 mm. Therefore, a microscope having a magnification of

$$(3.30/0.35) \times 45 = 424$$

will be adequate.

The microscope will need a minimum working distance (distance from the object being photographed to the bottom of the objective lens) of about 2 cm to allow for the thickness of the high-pressure glass window. Stereomicroscopes typically have large working distances to view the surface features of large objects and should be adequate for our needs. These microscopes have maximum magnifications ranging from x225 to x450.

Recording the Image. There are basically two methods of recording the bubble images for further processing: video (CCD) cameras and film photography. Digital cameras are similar to CCD cameras and share many of their advantages and disadvantages. Either could be used in Subtask 12.1, but Subtask 12.2 may require film photography. The video camera has two primary advantages: to record changing events (example: fluid flow in porous media), and capture an event that occurs infrequently (example: bubble coalescence). Neither of these is our primary concern in this task. Although further research into the possible use of a video camera will continue, the requirements imposed in Subtask 12.2. tend to support the use of film photography.

Digitizing the Image. If a CCD or digital camera is used, the image will already be in a digital format. Film will need to be digitized. Scanners exist that are

specifically designed for this task. An important consideration is the resolution of each process. This comparison is underway.

Processing of the Digital Images. Prior work processing digital images of rock grains in thin sections provides us with a possible method. The images were enhanced using Adobe PhotoShop, and the rock grain size distribution and aspect ratios were obtained using a program from the NIH designed for characterizing blood cells.

Static Cell. To verify the image acquisition and analysis process, a small static cell has been designed and constructed to trap a small quantity of foam at ambient temperature and pressure. A drawing of this cell is shown in figure 1. Both transmission and front surface illumination will be used. We suspect that transmission illumination will give the best results, but intensely absorbing or scattering material in the liquid phase may require front surface illumination.

9.3 Planned Activities

- Complete analysis of microscope requirements and availability, and purchase.
- Compare the ultimate resolution of the image-capturing methods.
- Complete analysis of camera types and purchase.
- Acquire a digital scanner if film photography is the best option.
- Identify the NIH software and download.
- Acquire Adobe PhotoShop.

Subtask 12.2. Develop/Test a Method for Dynamic Conditions

Based on the results of Subtask 12.1, design, construct and procure equipment to image bubbles in a flowing stream. This will most likely require a high-speed flash system to “freeze” the fluid motion for acquiring an image. Bubble images will be processed similarly to Subtask 12.1.

9.4 Project Status

Although work on this subtask will officially commence once Subtask 12.1 has been completed, some effort will be expended on this subtask to accelerate its completion.

Light Source. The primary consideration in this subtask will be obtaining bubble images with fluid flow of up to 6 ft/s. We must be able to “freeze” this motion to adequately photograph or record. This will require a device having either a very fast shutter or a short-duration flash. A short-duration flash would require that the shutter of the recording device (such as a camera) be open prior to, during and after the flash. Table 1 shows the maximum flash duration (or shutter speed) to capture the image. This table assumes a 5% blur, that is, the bubble moves a distance equal to 5% of its diameter during the image recording process. Based on this table, we must have a shutter/flash no slower than 0.3 μ s to “freeze” a 0.01 mm diameter bubble. To our knowledge, no camera exists capable of this shutter speed. Xenon strobes have flash durations longer than 7-10 μ s. Gas discharge lamps with flash durations down to 4 ns are known, but their light intensity is very low. A flash with a 0.1 μ s duration may exist. If this search is not

successful, we can either construct a short-duration flash, or purchase a nitrogen laser. Nitrogen lasers typically have flash lengths of 4 ns, but they emit in the ultraviolet. If we use a UV laser, we will need to direct this light (probably through a beam expander) into a cell filled with laser dye to absorb the UV light and re-emit light in the visible. Laser dyes have a high quantum efficiency (0.7-1.0) and a short radiative lifetime (5 – 20 ns), making them ideal light sources. Two potential problems to be aware of are photo bleaching and photo degradation. Recording the Image. Conventional cameras are ideally suited for operating with a very short duration flash. The procedure is similar to that used to photograph lightning at night: open the shutter, trigger the lamp or laser to flash, close the shutter. The region around the photographic cell must be completely dark before and after the flash. Based on discussions with those knowledgeable in CCD and video cameras, this photographic process is very difficult for video cameras.

9.5 Planned Activities

- Continue efforts to locate a gas discharge lamp with a sufficiently short flash duration.

Subtask 12.3. Install the Foam Bubble Size, Shape and Distribution Monitoring System on the ACTF

Modify the prototype developed in Subtask 12.2 to operate on the ACTF. Install the system and verify its operation.

Project Status

No activity is planned for this subtask until more progress is made on Subtask 12.2.

Planned Activities

None at this time.

Figure 9.1. Static Foam Cell for Bubble Photography

Figure 9.2. Static Foam Cell For Bubble Photography

Materials:

- 6-32x1/2" SS machine screw (12 ea)
- #6 Nylon washer (6 ea)
- 1/8"x3/4" Al bar stock (8")
- Gasket material (Silicone RTV)
- 4"x4"x1/2" Lexan
- 2"x2" glass diffuser
- 2"x2" optical plastic slide
- 5"x1/4" dia. SS tubing (2 ea)

Table 1. Exposure Time/Flash Duration (μs)

Fluid Velocity	Bubble Size			
(ft/s)	1000 μm	100 μm	10 μm	1 μm
6	27	2.7	0.27	0.027
2	82	8.2	0.82	0.08
0.5	330	33	3.3	0.33
0.1	1600	160	16	1.6

Note: 1000 μm = 1 mm

10. TECHNOLOGY TRANSFER

Several activities including, Advisory Board Meeting with ACTF-JIP member companies, Oil and Gas conference presentation and individual visits and presentations to oil and service company members have been conducted since May 1998. Following section summarizes these activities.

a- Advisory Board Meeting with ACTF-JIP Members

An Advisory Board Meetings with ACTF-JIP members and prospective members was organized May 11, 1999 (A list of Attendees for May 1999 Meeting is presented in Exhibit A). Presentations on the progress of flow loop development, research projects, modified ACTF five-year plan and proposed budget were made to industry members. The objectives and the scope of the ACTF project was well received by the industry members. Discussions were held and the industry members provided their inputs on various issues of ACTF project.

b- Poster Presentation at the 1999 Oil and Gas Conference

A poster presentation of the ACTF-Project Development and Research Status has been made at the 1999 Oil and Gas Conference organized by U.S. Department of Energy. The conference was held on June 28-30, 1999 in Dallas, Texas.

c- Meetings with Oil and Service Company Members

Currently there are 5 industry members of ACTF-JIP namely, Chevron, Halliburton, Statoil, Japan National Oil Company, and Dowell-Schlumberger. Efforts have been spent continuously to increase the number of industry members supporting the ACTF projects.

EXHIBIT A

List of Attendees to ACTF-JIP Advisory Board Meeting on May 11, 1999

THE UNIVERSITY OF TULSA
DEPARTMENT OF PETROLEUM ENGINEERING
ACTF/JIP
ADVISORY BOARD MEETING
May 11, 1999

NAME	COMPANY	FAX # / E-MAIL ADDRESS
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