CUTTINGS TRANSPORT WITH FOAM IN HORIZONTAL AND INCLINED WELLBORES

RESEARCHER

- M. Evren Ozbayoglu

A Petroleum and Natural Gas Engineer graduated from the Middle East Technical University, Ankara, Turkey in 1996 and took his M.S. degree in 1998 from the same university. Worked as a research assistant between 1996 and 1998 at Petroleum and Natural Gas Engineering Department of Middle East Technical University. Joined the Department of Petroleum Engineering of University of Tulsa, TUDRP, as a Ph.D. student and Graduate Assistant in the fall semester of 1998.

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 backpressure) for effective cuttings transport with foam flow in inclined and horizontal wellbores.

SCOPE

1. Extensive literature review of relevant works on foam rheology, foam flow models and cuttings transport.
2. Collection of data from experiments carried out with TUDRP's low pressure, ambient temperature flow loop. Experimental program will include:
   - Foam flow without cuttings to investigate foam flow properties, the applicability of flow behavior and foam flow models.
   - Cuttings transport with foam at different values of ROP and inclination angle.
3. Development of a mechanistic model for cuttings transport with foam and verification of model by using experimental data.

DELIVERABLES

1. Advisory Board Meeting Progress Reports and Final Report.
2. Experimental data on foam rheology and cuttings transport efficiency with foam.
3. Mathematical modeling of foam flow behavior and cuttings transport with foam.
4. A computer program for practical application.

EXPECTED COMPLETION DATE

Fall, 2001.

WORK DONE

Literature Survey	Rheology of Foam	70%
	Cuttings Transport Phenomena	20%
Modification of Loop for Foam Flow	Plan	95%
	Construction	0%
Experiments Performed		0%
Model Developed	Rheology Review	30%
	Cuttings Effect	0%
Computer Simulator	Without Cuttings	20%
	With Cuttings	0%

PRESENT WORK

Development of the computer program for foam hydraulics calculations is in progress. Source code of Blauer[7] et al, Sanghani[8], Beyer[6] et al. and Sporker et al[19]. models are completed, but not verified yet. The source code for the other models will be completed in the near future. The design of the TUDRP-LPAT flow loop modification for foam flow is complete and the purchase of the necessary equipment is in progress.

FUTURE WORK

The literature survey on foam rheology, foam flow models and cuttings transport will continue. The equipment needed to modify the loop for foam flow with cuttings will be purchased and installed. Then, experiments will be performed using different foam properties, with and without cuttings. Mathematical modeling of foam flow will continue. Finally, a computer program will be prepared for field applications.

TABLE OF CONTENTS

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, etc[1]. 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 angle[2]. 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 phase[3]. 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.

APPROACH

A complete 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.

LITERATURE REVIEW

Foam Behavior and Rheology

Khan[4] 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.

Mitchell[5] 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 al[6] 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 al[7] 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.

Sanghani[8] 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 Kuntamukkula[9] 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 Niles[10] 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 Economides[11] 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;

$$\varepsilon_s = \frac{\rho_L}{\rho_F} \tag{2}$$

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 :

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

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 γ is the shear rate. The volume equalized Bingham plastic is given by :

$$\tau = \left[\frac{\tau_o \varepsilon_s}{|\gamma|} + \mu_p \right] \gamma \qquad |\gamma| > \tau_o \varepsilon_s \qquad (4)$$

$$\gamma = 0 \qquad \Rightarrow \qquad |\tau| > \tau_o \varepsilon_s$$

where τ_o 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.

Enzendorfer[12] 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's[13] classical slip correction was not applicable, but a method developed by Jastrzebski[14] 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 principle [8]. 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 al[15] 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-Jarstrzebski's method[28]. 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 Mitchell[16] 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.

Lord[17] 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.

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

where

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

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

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

m is mass, *M* is molecular weight of gas, *P* is the absolute pressure, *R* is the gas 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 Ikoku[18] 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 al[19]. 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 Medley[20] 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 al[7]

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

$$Q = \frac{\pi \Delta P D^4 g_c}{128 \mu_p L} \left(1 - \frac{4}{3} \frac{\tau_y}{\tau} + \frac{1}{3} \left(\frac{\tau_y}{\tau} \right)^4 \right) \tag{6}$$

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

$$Q = \frac{\pi \Delta P D^4 g_c}{128 \mu_e L} \tag{7}$$

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

$$\mu_e = \mu_p + \frac{g_c \tau_y D}{6v} \tag{8}$$

They used the same method that Mitchell[5] 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 Krug[16] for the determination of the plastic viscosity and yield strength.

The foam density is defined by

$$\rho_f = \rho_l (1 - \Gamma) \tag{9}$$

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

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

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

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

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

$$\rho_f = \rho_l (1 - \Gamma) + \rho_g \Gamma \tag{12}$$

The pressure loss gradient is calculated by using the empirical equation

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

Beyer et al[6]

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

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

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)

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

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

For $\tau_w \leq 0.0024$ psi

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

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

For $\tau_w > 0.0024$ psi

$$v_S = 25.8 LVF + 357(\tau_w - 0.0024) \qquad 0.02 \le LVF \le 0.1 \tag{18}$$

$$v_S = 1.1 + 14.8 LVF \qquad 0.1 \le LVF \le 0.25 \tag{19}$$

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

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

The fluidity of foam is expressed as

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

$$v_F = 0 \tag{21}$$

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

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

The Bingham viscosity of the foam is given by

$$\mu_o = \frac{1}{7200 LVF + 267} \tag{23}$$

$$\mu_o = \frac{1}{2533 LVF + 733} \tag{24}$$

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

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

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 $u=\varepsilon u_o$, 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

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

The principle states that all volume equalized shear-stress volume equalized shear-rate points obtained in different qualities and different geometries 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

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

The VE Fanning friction factor is

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

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

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

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

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

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

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

The foam density is described as

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

The superficial velocity derived from continuity is

$$u = \frac{c}{\rho} = \frac{ac}{p} + bc \tag{33}$$

and

$$du = -\frac{ac}{p^2}\,dp \tag{34}$$

So, differential mechanical energy balance equation for horizontal flow becomes

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

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

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

The specific volume of foam is defined as

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

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

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

where the term in parenthesis is the compressibility factor.

So, equation of state for the foam is obtained as

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

where

$$a = w_g R \frac{T}{M_g} \tag{40}$$

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

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

$$u = cv = \frac{ac}{p} + bc \tag{42}$$

where

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

$$du = -\frac{ac}{p^2}\,dp \tag{44}$$

so, substituting into mechanical energy balance gives

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

Gardiner et al[15]

They used "Volume Equalized Principle" proposed by Valko & Economides[11]. 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

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

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

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

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

$$Q_{calculated} = 2\pi\int_{0}^{R} urdr = \pi R^{2}\left\{u_{slip} + \frac{n}{3n+1}\left[\left(-\frac{dp}{dx}\right)\frac{R^{n+1}\varepsilon^{n-1}}{2k}\right]^{\frac{1}{n}}\right\} \tag{48}$$

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

$$\beta = \frac{\beta_c}{D} = \frac{u_{slip}}{\tau_w} \tag{49}$$

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

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

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 Ikoku[18] 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 Sobey[22] 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 Santana[24] 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 Clark[2], 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 Chukwu[25] 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 Shirazi[1] 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 Rahman[26] 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.

Sanchez[27] 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.

EXPERIMENTAL SETUP

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 flow loop needs to be modified for foam flow with cuttings as shown in Fig.1. 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 (Fig.2). 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. The pH of the foam will be decreased from 10 to 6 by injecting acid in order to break the foam. Gas phase and liquid phase will be separated in a liquid-gas separator, and the gas will be vented (Fig.3). The liquid + surfactant mixture will be collected in collection tank, and pH will be increased from 6 to 10 to activate the surfactant. Corrosive chemical resistant, low-flow centrifugal pumps with maximum capacity of 20 gpm will be used both for injecting acid and base solutions. Then, the mixture will be pumped back to generation tank, and cycle will be completed. So, the amount of surfactant that will be used for the experiments will be lowered as much as possible.

The amount of acid injected will be controlled by an adjustable control-valve. The volumetric flow rate of acid required will be calculated, and the rate will be adjusted according to the reading from the flow-meter inserted just after the control-valve (Fig.4). The base injection will be controlled by a pH controlled pump unit automatically. The pH level in the collection tank will be measured continuously by the pH control unit, and the pump will turn on and off according to the signal it receives. the liquid + surfactant mixture will be pumped to the generation tank as soon as required pH level is achieved in the tank.

The separator has screen trays inside it, and a gas vent opening at the top. A liquid level will be kept constant at the bottom of the separator in order to keep any gas enter into the line that goes to the shale shaker. The separator has an ability to hold the liquid + gas + surfactant + acid + cuttings solution for a few seconds for complete breaking.

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.

REMARKS & 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

REFERENCES

1. Pilehvari, A.A., Azar, J.J., and Shirazi, S.A., "State-Of-The-Art Cuttings Transport in Horizontal Wellbores," SPE 37079, Calgary, November 18-20, 1995

2. Clark, R.K., "A Mechanistic Model for Cuttings Transport," SPE Paper 28306, New Orleans, September 25-26, 1994

3. GSI, "Underbalanced Drilling Manual," 2.27-2.130, GSI, 1997

4. Khan, S.A., "The flow of foam through porous media," M.S. Thesis, Stanford University, Stanford, 1965

5. Mitchell, B.J., "Viscosity of Foam," Ph.D. Dissertation, University of Oklahoma, Norman, 1969

6. Beyer A.H., Millhone R.S., Foote R.W., "Flow Behavior of Foam as a Well Circulating Fluid," SPE Paper 3986, San Antonio, October 8-11, 1972

7. Blauer R.E., Mitchell B.J., Kohlhess C.A., "Determination of Laminar, Turbulent and Transitional Foam Flow Losses in Pipes," SPE Paper 4885, San Fransisco, April 4-5, 1974

8. Sanghani, V., "Rheology of Foam and Its Implications in Drilling and Cleanout Operations," M.S. Thesis, University of Tulsa, Tulsa, 1982

9. Heller, J.P., and Kuntamukkula, M.S., "Critical Review of the Foam Rheology Literature," Ind.Eng.Chem.Res. 26, 318-325, 1987

10. Cawiezel, K.E., and Niles, T.D., "Rheological Properties of Foam Fracturing Fluids Under Downhole Conditions," SPE 16191, Dallas, March 2-3, 1987

11. Valkó, P., and Economides, M.J., "Volume Equalized Constitutive Equations for Foamed Polymer Solutions," Journal of Rheology, 6, 1033-1055, 1992

12. Enzendorfer, C., “Pipe viscometry of foams,” Journal of Rheology, 2, 345-358, 1995

13. Mooney, M., “Explicit Formulas for Slip and Fluidity,” Journal of Rheology, 2, 210-222, 1931

14. Jastrzebski, Z.D., “Entrance Effects and Wall Effects in an Extrusion Rheometer During the Flow of Concentrated Suspensions,” Ind.Eng.Chem.Fund. 6, 445-453, 1967

15. Gardiner B.S., Dlugogorski B.Z., Jameson G.J., “Rheology of Fire-Fighting Foams,” Fire Safety Journal, 1988

16. Krug, J.A., and Mitchell, B.J., “Charts Help Find Volume Pressure Needed for Foam Drilling,” OGJ, Feb. 7, 61-64, 1972

17. Lord, D.L., “Analysis of Dynamic and Static Foam Behavior,” JPT, Jan., 39-45, 1981

18. Okpobiri, G.A., and Ikoku, C.U., “Experimental Determination of Solids Friction Factors and Minimum Volumetric Requirements in Foam and Mist Drilling and Well Cleanout Operations,” Final Report, University of Tulsa, Tulsa, 1982.

19. Spörker, H.F., Trepess, P., Valkó, P., and Economides, M.J., “System Design for the Measurement of Downhole Dynamic Rheology for Foam Fracturing Fluids,” SPE paper 22840, Dallas, Oct. 6-9, 1991

20. Liu, G., and Medley, G.H., “Foam Computer Model Helps in Analysis of Underbalanced Drilling,” OGJ, July 1, 114-119, 1996

21. Martin, M., Georges C., and Konirsch O., “Transport of Cuttings in Directional Wells,” SPE/IADC Paper 16083, New Orleans, March 15-18, 1987

22. Gavignet, A.A., and Sobey, I.J., “Model Aids Cuttings Transport Prediction,” JPT, September, 916-921, 1989

23. Larsen, T.I., “A Study of the Critical Fluid Velocity in Cuttings Transport for Inclined Wellbores,” M.S. Thesis, University of Tulsa, Tulsa, 1990

24. Martins, A.L., and Santana, C.C., “Evaluation of Cuttings Transport in Horizontal and Near Horizontal Wells – A Dimensionless Approach,” SPE Paper 23643, Caracas, Venezuela, March 8-11, 1992

25. Belavadi, M.N., and Chukwu, G.A., “Experimental Study of the Parameters Affecting Cuttings Transportation in a Vertical Wellbore Annulus,” SPE 27780, Long Beach, March 23-25, 1994

26. Nyugen, D., and Rahman, S.S., “A Three Layer Hydraulic Program for Effective Cuttings Transport and Hole Cleaning in Highly Deviated and Horizontal Wells,” IADC/SPE Paper 36383, Kuala Lumpur, Malasia, September 9-11, 1996

27. Sanchez, R.A., “Modeling of Drilled Cuttings Bed Erosion in Highly Inclined Wells,” M.S. Thesis, University of Tulsa, Tulsa, 1997

28. Jastrzebski Z., “Entrance Effect and Wall Effect in Rheometer During the Flow of Concentrated Suspension,” Ind. Eng.Chem.Res. 6, 445-454, 1967

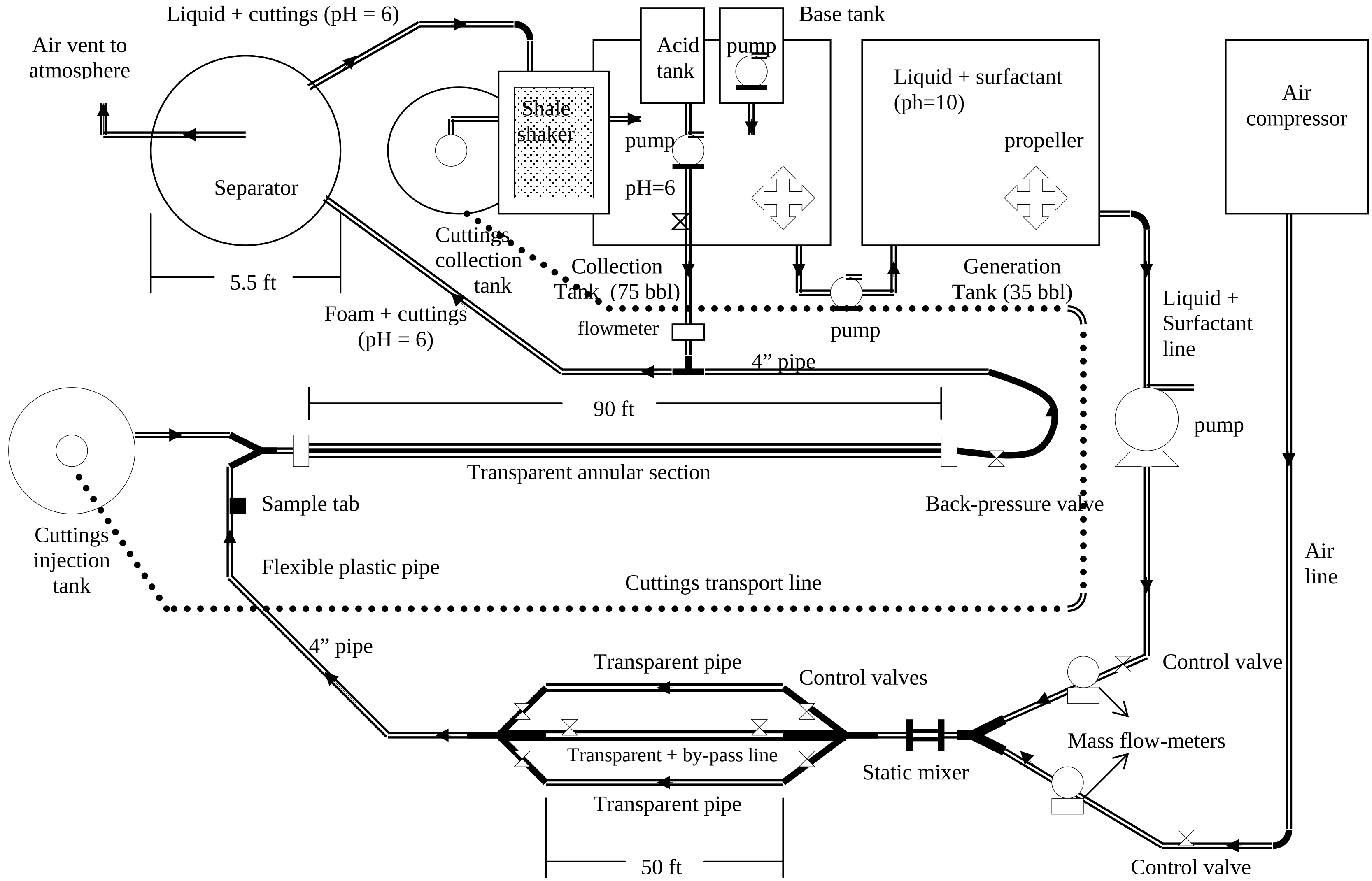

Figure 1 – TUDRP-LPAT flow loop modification for foam flow

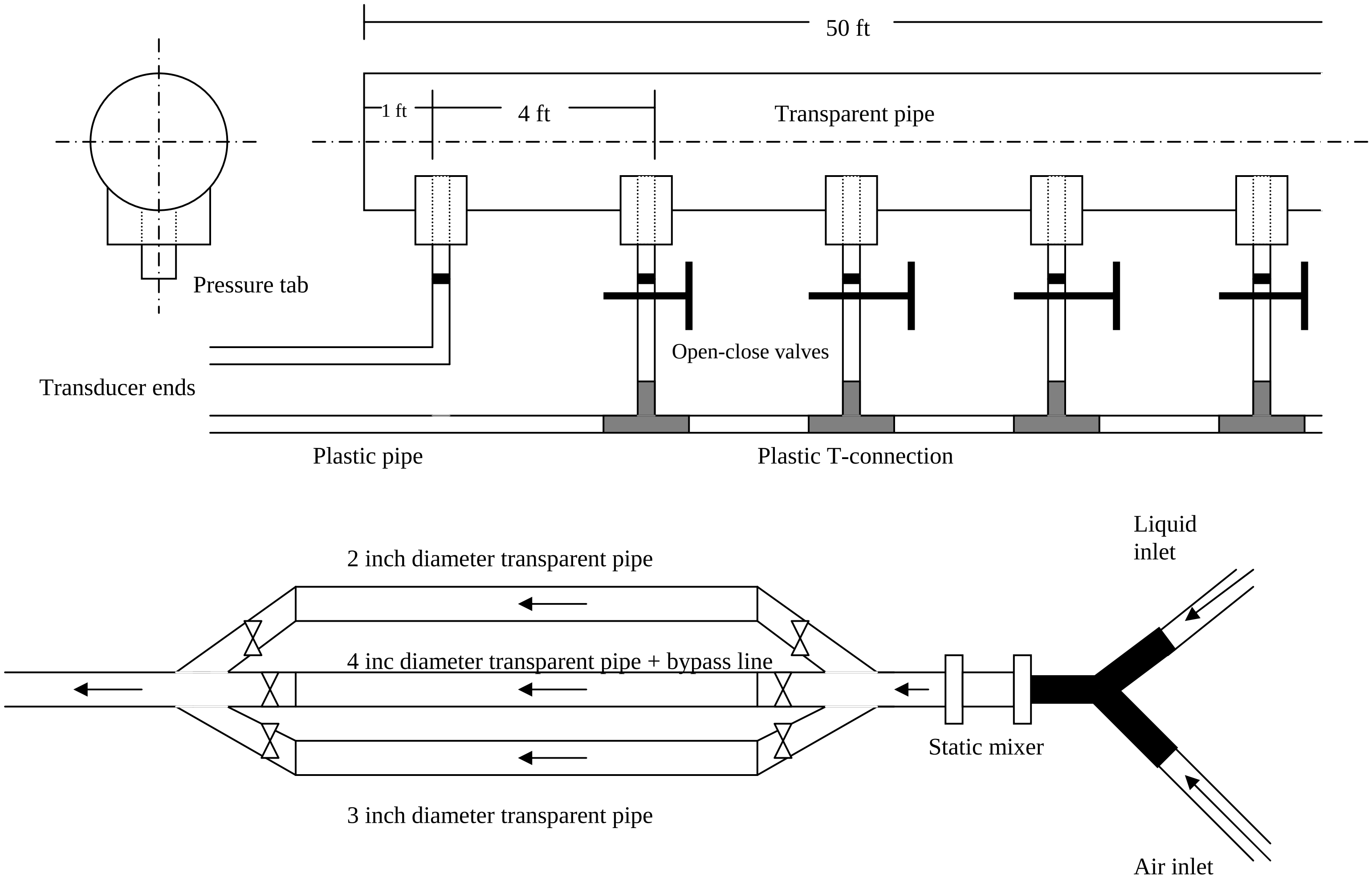

Figure 2 – Pipe viscometer section

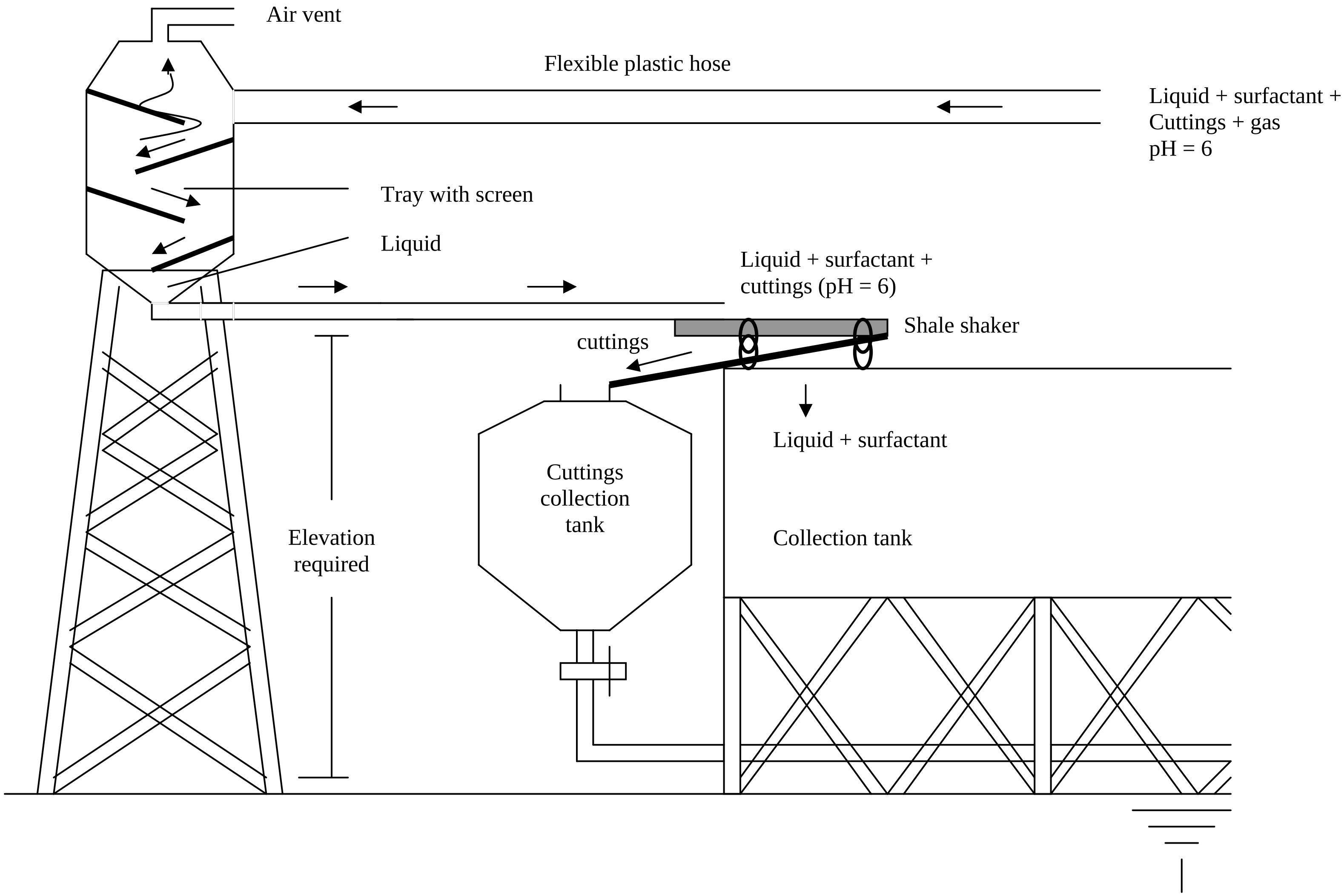

Figure 3 – Liquid – gas – solid separation process

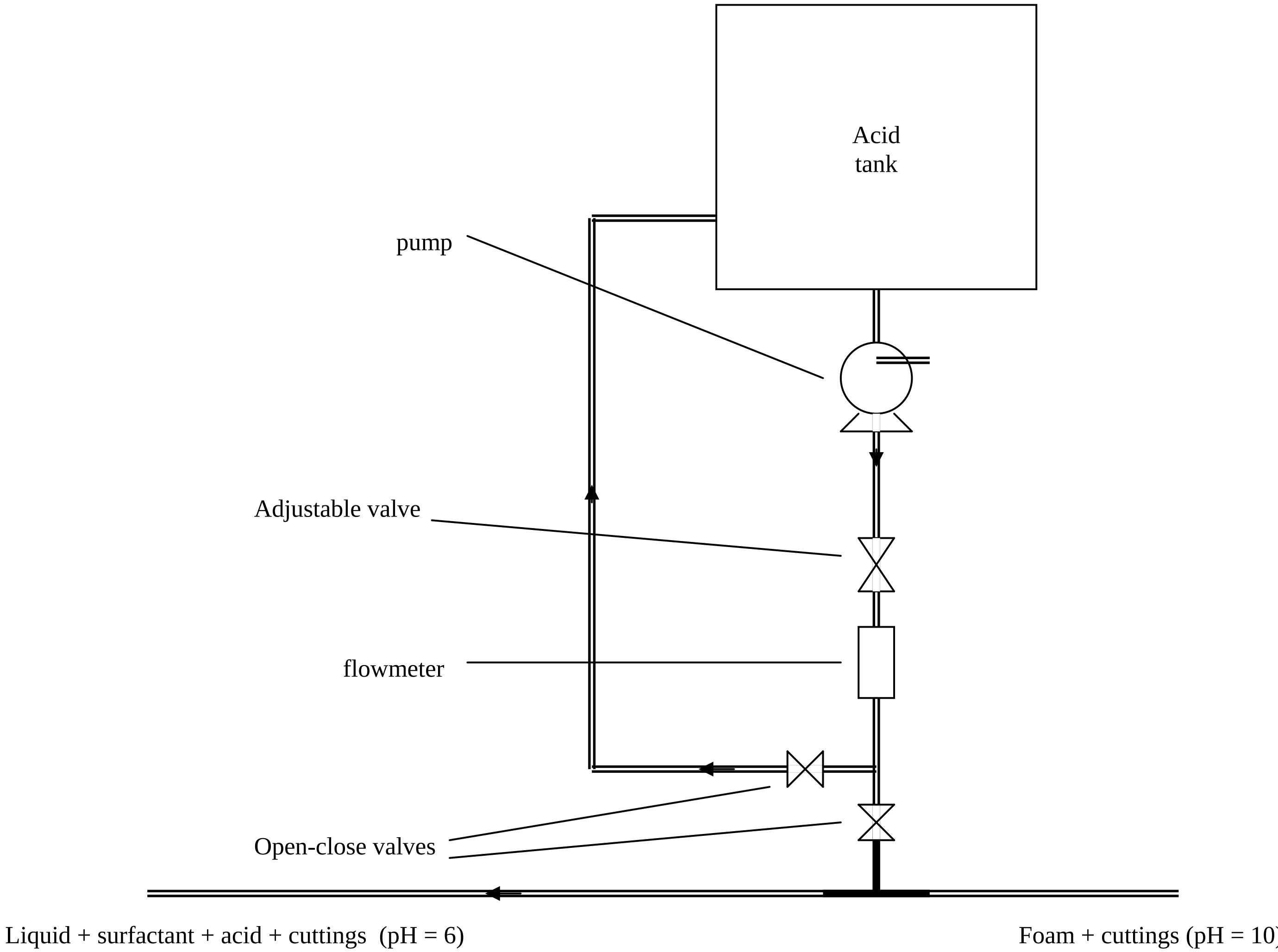

Figure 4 – Acid injection process