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UNIVERSITI TEKNOLOGI PETRONAS

FILL REMOVAL FROM HORIZONTAL WELLBORE USING FOAM IN COILED TUBING

by

JAVED AKBAR KHAN

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FILL REMOVAL FROM HORIZONTAL WELLBORE USING FOAM IN COILED TUBING

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A Thesis

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BANDAR SERI ISKANDAR,

PERAK

NOVEMBER2013

DECLARATION OF THESIS

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I JAVED AKBAR KHAN

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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DEDICATION

To my late father Muhammad Akbar Khan and my beloved mother Ghulam Sakina

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ABSTRACT

Coiled tubing is extensively used in oil industry to clean the wellbore to increase the productivity of oil/gas well by removing the fill/sand downhole. Well cleanup operation for large diameter well with low bottomhole pressure is problematic and common cleanout fluids are not effective as a circulation fluid due to severe pressure losses and low suspension capability. In order to mitigate such effect, foam is used as a circulation fluid because it has the highest suspension power. Foam is formed by mixing water, air and additive. Due to complexity of foam rheology, it is challenging to accurately predict foam-solids flow behaviour during coiled tubing cleanout operation. Hence, the objective of the present research is to analyze the flow circuitry where the foam and fill mixed at annulus bottom and circulated back through the cased annulus. In order to effectively remove the fill from the bottomhole to achieve a clean well, fill transport in horizontal annulus is analysed using ANSYS CFX-14 software. Horizontal well geometries were created for fill concentration analysis at various foam qualities and velocities. The flow is assumed to be in pseudo-steady state condition. Herschel-Bulkley viscosity model is assumed for the foam behaviour. The results of the study showed that the foam velocity, diameter ratio and particle size are found to be the deciding factors for the particle depositional pattern. Fill removal is observed to be most efficient at 4-6 ft/sec of foam velocities for particle diameter size 2 mm and below. It is noticed that a foam quality of 90% is required to remove particle size of 2 mm and above. As expected, fill concentration is found to be inversely proportional to fill diameter. Surprisingly, it is also discovered that fill diameter has insignificant effect on pressure drop. The diameter ratio of the coiled tubing to cased hole is found to be the most significant effect on annulus fill concentration and pressure drop. It is noticed that diameter ratio has high effect on particle removal when foam quality is 70 %. It is also observed that pressure drop increases linearly with the increase of foam quality.

ABSTRAK

Tiub bergelung digunakan dengan meluas dalam industri minyak untuk pembersihan lubang telaga bagi meningkatkan produktiviti dengan mengeluarkan isi (partikel pasir) dari dasar lubang. Operasi pembersihan telaga minyak berdiameter besar dan tekanan dasar lubang rendah adalah paling bermasalah dan cecair pencuci biasa tidak berkesan sebagai cecair edaran disebabkan oleh kehilangan tekanan yang teruk dan daya apungan yang rendah. Dalam usaha untuk mengurangkan kesan itu, buih digunakan sebagai cecair peredaran kerana ia mempunyai daya apungan yang tinggi. Buih dibentuk dengan pencampuran air, udara/gas dan bahan tambahan. Disebabkan kerumitan reologi buih, ia merupakan sesuatu cabaran untuk meramal tingkah laku aliran buih-pepejal semasa operasi pembersihan tiub bergelung. Objektif kajian ini adalah untuk menganalisis litar aliran di mana buih dan isi pepejal bercampur di bahagian bawah lubang telaga dan diedarkan semula melalui anulus. Untuk membersihkan isi pepejal secara berkesan dari dasar lubang, pergerakkan isi secara horisontal dianalisis dengan ANSYS CFX -14. Telaga geometri horisontal direkabentuk untuk menganalisis kepekatan pelbagai kualiti buih dan halaju. Aliran buih dianggap berada dalam keadaan pseudo mantap. Model kelikatan Herschel - Bulkley dianggap sebagai tingkah laku buih. Keputusan kajian menunjukkan bahawa halaju buih, nisbah diameter dan saiz pepejal adalah faktor penentu corak pemendapan zarah. Penyingkiran isi adalah paling berkesan dalam julat halaju buih 4-6 kaki sesaat untuk saiz pepejal 2 mm dan ke bawah. Kualiti buih setinggi 90% diperlukan untuk menyingkirkan saiz pepejal 2 mm dan ke atas. Agak menakjubkan, didapati bahawa diameter isi mempunyai kesan yang kurang ketara ke atas kehilangan tekanan. Nisbah diameter didapati mempunyai kesan paling ketara ke atas kepekatan isi dan kehilangan tekanan di dalam annulus. Selain itu, nisbah diameter didapati menpengaruhi penyingkiran zarah apabila kualiti buih adalah 70%. Didapati bahawa kehilangan tekanan meningkat secara linear dengan peningkatan kualiti buih.

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CHAPTER 1

INTRODUCTION

1.1 Background

Coiled tubing is extensively used in oil industry to clean the wellbore to increase the productivity of oil/gas well by removing the fill/sand downhole.

1.1.1 Fill removal

The removal of fill (produced sand, scale and fines) from production well has been the common application of coil tubing services. The primary reason for fill removal is to restore the productivity of oil/gas well. It can be seen from one example that production rate is increased after cleaning operation as shown in Figure 1.1. Additionally, fill removal is necessary to permit the passage for operational tools and to remove the choking material for completion operations.

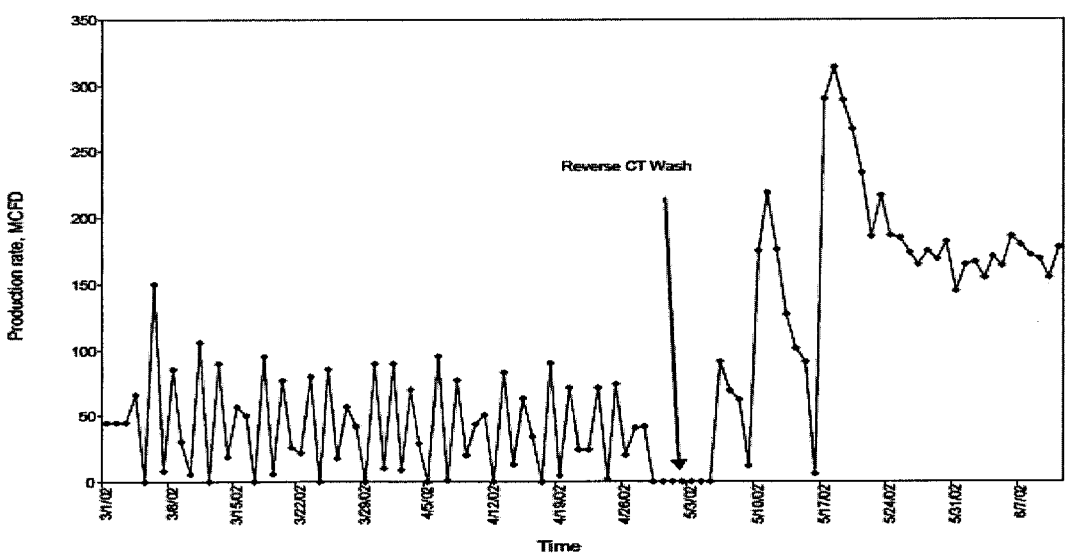

Figure 1.1: Production rate after fill removal from vertical well in USA [1]

1.1.2 Fill cleaning methods

Several techniques, such as dual string system, pump to surface bailing have been developed in the past. One of the most common fill removal operation is running in with Coil Tubing (CT) and circulating out the solids with carrying fluids. Coiled tubing is considered as one of the most time efficient and cost effective method for fill removal in the industry. Removing wellbore fill is one of the most frequently use and yet challenging issue in coil tubing unit for wellbore cleanup. It forms 50% of coil tubing services worldwide [2]. Coil Tubing has two circulation modes to remove fine particles downhole, namely the forward and reverse circulation mode, as illustrated in Figure 1.2. In the forward circulation mode, fluid is pumped through the coil tubing and circulated back to the main reservoir via the annulus. In the process, the returning fluid carries with it fines which are captured downhole. It is the most common cleanout operations used in coil tubing unit. On the other hand, reverse circulation mode involves pumping fluid down the tubing annulus and the fluid-solid suspension is routed back to the main reservoir via the coil tubing string. This method is most commonly used for large particles cleanout.

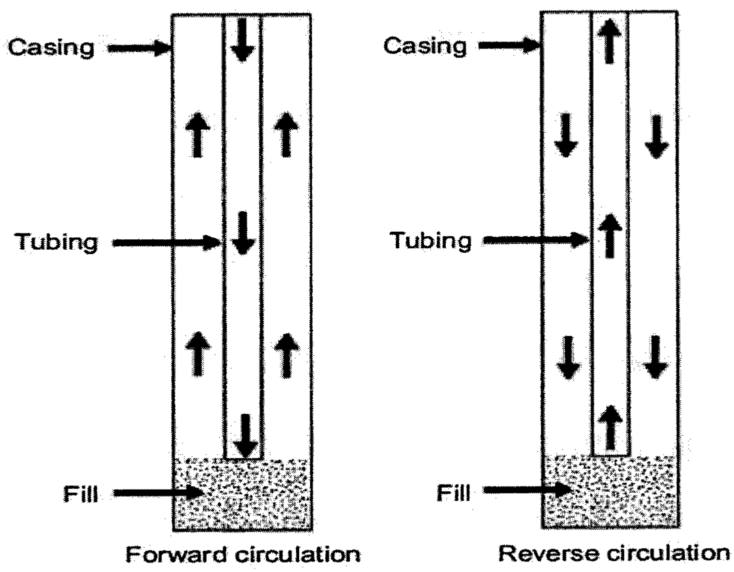

Figure 1.2: Two circulation mode for sand cleaning [3]

The cleaning agent, typically water, brine or diesel, is pumped through a nozzle via the coiled tubing string. The jetting fluid from the nozzle penetrates the fill downhole and in the process, entrapping the solid particles as suspension, which is to be circulated out through the production tubing annulus. The annulus fluid velocity should be greater than the settling velocity of fill material during the return loop. This is to ensure that the buoyancy force of the cleaning agent is higher than the gravity force of the particles.

1.1.3 Fill cleaning from horizontal well

Fill removal is a major issue in high angle and horizontal wells [4] as shown in Figure 1.3. In this situation, there is a tendency to deposit a solids bed in the lower part of the annulus. The velocity of cleanout fluid is a critical factor in sand removal. To achieve the necessary cleanout velocity for high head in horizontal well, high surface pumping pressure and high fluid flow rate are required. However, the pump head cannot be continuously sustained at high pressure beyond a certain period due to overheating. High fluid flow rate is another issue which adds to additional cost and logistical problem for lifting the solid particles.

Therefore, the selection criteria of cleaning method have to take into account these issues, including bottomhole pressure, borehole radius, particle size and formation potential. The only solution to this problem is to increase the velocity of fluid in annulus that will minimize the concentration of particles in annular section. Unfortunately, the increment of cleanout fluid velocity is insufficient due to fluid friction at coil tubing wall and surface equipment. Thus, fluid with high suspension power is required, even for low circulation velocity.

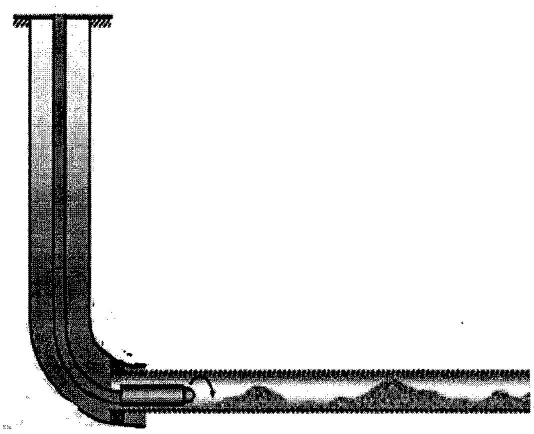

Figure 1.3: Fill removal from horizontal well [1]

1.1.4 Fill bed formation

When removing the fill, with the coil tubing in the production pipes, the annular velocities and the rate of slip velocity of particles are such that, if provided enough circulation time, the particles will be removed from the well [5]. The circulation can take long time. But, when coil tubing inserted in the large casing then fluid annular velocity cannot be maintained like small diameter wellbore. In this case annular velocities are less than solid particle slip velocity, hence, making a wellbore fill removal operation a challenging objective. Also, in large wellbore where there is usually lower fluid annular velocity, sand settles on due to gravity, creating a stable fill bed. Circulation fluid removes the fill over the top of the bed, leaving more particles up the hole as shown in Figure 1.4. After a short interval, the flow area over the fill bed is minimized such that the fluid with sustained particles will pass over the top of the bed. The newly sustained particles will also deposit on the already formed bed. This small area in the region over the bed will cause a drop in the annulus velocity, allowing further fill to be deposited. In this condition, no net cleaning is achieved, the fill form an equilibrium bed throughout the wellbore.

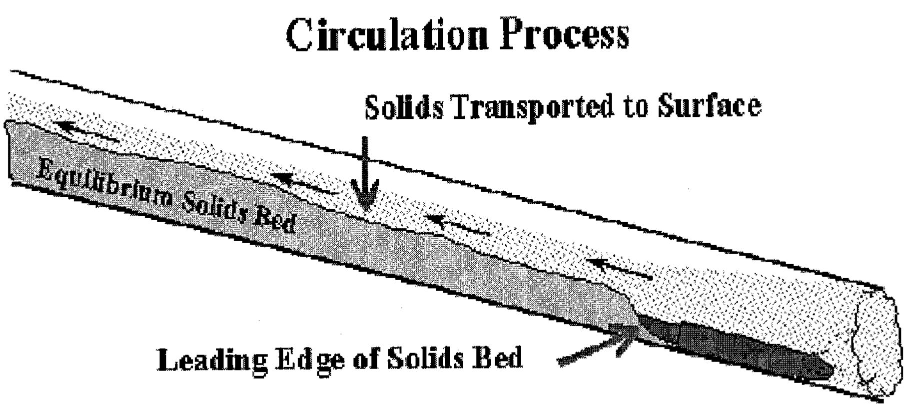

Figure 1.4: Fluid circulation in deviated well [1]

It is observed that the ability to pick up, suspend and transport solids from high angle inclination wells was entirely limited by annular velocity [6]. Solution can be obtained for the above mentioned problems if foam is used as a circulation fluid. Foam has been proven an effective and economical cleaning agent in low bottom hole pressure well operations [1]. One of the primary advantages of foam is the capacity for solid particles transport is that, its structure does not allow the fallback of solids, even under no circulation conditions.

1.2 Coiled Tubing operation setup

Presented in Figure 1.5 is a common equipment configuration for use in the fill removal with foam. The foam has to be prepared in advance before beginning the operation; this gives the foam enough residence time for the required foam characteristics to be achieved. The foam is generated by mixing in a gas phase with a foaming agent and a base fluid. Water and oil are the most typical kind of base fluids. The foaming agent (0.5 to 1% by volume) is a surfactant. It is used to lower the surface tension between the gas and the base fluid [3].

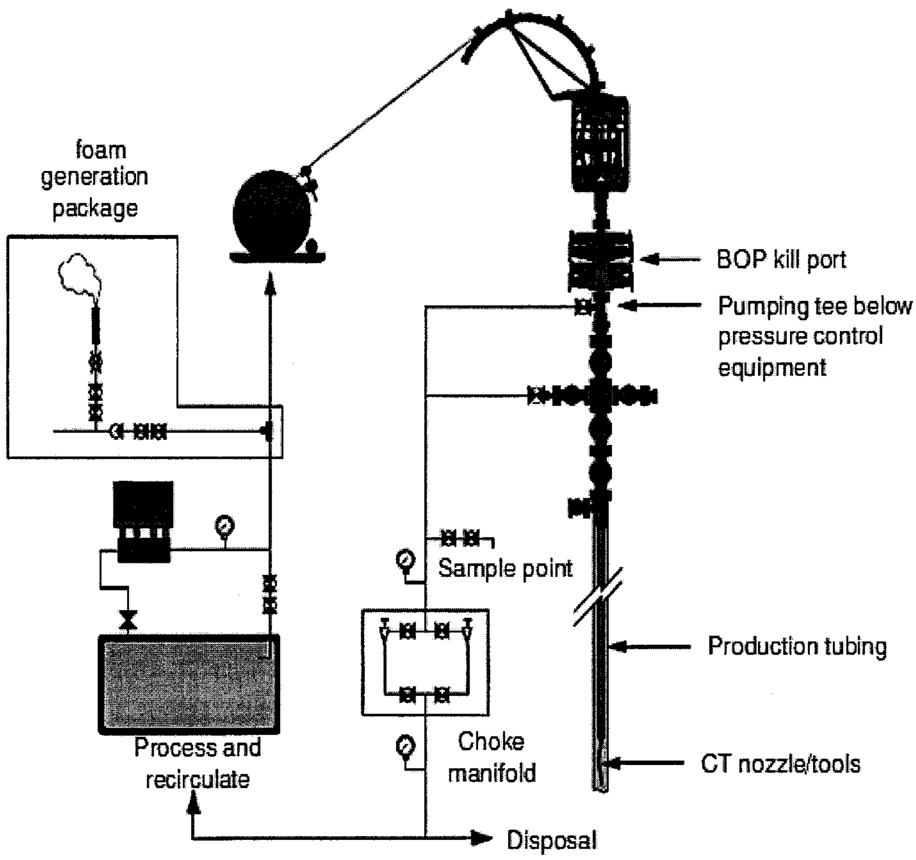

Figure 1.5: Typical foam equipment configuration for fill removal [7]

1.3 Problem statement

Improper hole cleaning leads to accumulation of solid particles in the lower side of the wellbore, which in turn results in costly fill removal operation such as:

a. Increase of coil tubing sticking potential due to the sedimentation of the solid particles inside the annulus.

b. Higher drag which requires additional force to push in and push out the coil tubing from the wellbore.

c. Slower rate of penetration over fill due to stickiness of coil tubing in the annulus.

d. Higher frictional pressure losses due to restriction in the circulation fluid flow.

During sand cleanout operations using foam, predicting foam flow velocity suitable to clean the wellbore is a major challenge. This becomes more complex when polymer is added to foam to improve the suspension of foam [1]. Foam flow in horizontal well is different from vertical well because the particle settling velocity is perpendicular to foam flow direction. Hence, fill tends to settle on the lower side of wellbore [8]. As a result, the solid transport mechanism is different for horizontal well. The model developed for vertical well is therefore not valid for horizontal wellbore [3].

Studies on solid particles transport using foam are very limited. An in depth knowledge of foam hydraulics is necessary to better understand the mechanism of fill transportation in horizontal wellbore geometry. Foam has the ability to keep the solid particles suspended and remove it out of well.

1.4 Research objectives

The overall research objective for this study is to investigate the foam-solid transport in horizontal wellbore when there is no rotation of inner tubing which is penetrating in the fill surface at a rate of 1-ft/min . This overall objective leads to specific objectives which are:

1. To investigate solid transport in horizontal annulus with different foam velocities and qualities and to predict the sand settlement using numerical analysis.
2. To study the effect of different qualities and velocities of foam-solid flow on the pressure loss during cleaning operation.
3. To analyze the effects of particles size and CT/Annulus diameter ratios on the fill concentration and pressure drop along horizontal wellbore.

1.5 Scope of research

Scope of study:

1. Study is focused on the forward circulation of fluid in the wellbore
2. Fill removal study is carried out for large size wellbore
3. Fill concentration is observed by keeping coiled tubing concentric in the wellbore.
4. Numerical Analysis of foam-solid flow using ANSYS-CFX®
5. Model validations and analysis of fill concentration at different CT/Annulus diameters and variable particle seize.

1.6 Outlines of thesis

Appropriate analysis is required to investigate the fill removal from horizontal wellbore during coiled tubing cleanup operation with foam. Experimental study of foam-solid transport in the horizontal wellbore is taken to validate the numerical model. The contributions of present study are presented in five chapters. An overview of each chapter is given below.

Chapter one introduced the basic concept of fill removal with coiled tubing, problem statement, objectives and scopes of research.

Chapter two presents the review of the available studies conducted by various researchers in the area of foam-solid transport from wellbore.

Chapter three outline the methodology used for the fill transport with foam. The assumptions, mathematical formulation and boundary conditions are discussed in detail in this chapter.

Chapter four presents the detail results and discussion of the present study. It include the validation of model, fill concentration along the wellbore, fill bed formation, effect of different foam qualities and velocities on fill removal. It also include the effect of CT/Annulus diameter ratio on fill concentration and pressure drop by varying foam velocity, quality and fill size.

Chapter five draws conclusion and makes recommendation from the analysis conducted.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Many studies have been carried out in relationship with prediction of pressure drop and solid particles transport in a horizontal wellbore during wellbore cleanup operation with foam. The following literature review are related to coil tubing cleaning operation using foam. Coil Tubing cleaning is required to enhance the production of oil/gas well. Use of foam in petroleum industry is an increasing trend because of the desirable properties that it exhibits. The reduced density of the foam fluids, their high solids carrying capacity, and their performance on eliminating filtrate and circulation losses are among these desirable properties during cleanup operations.

2.2 Rheology and hydraulic properties of foam

Foams are complex mixtures of gas, liquid and a surfactant whose rheological properties are strongly influenced by parameters like temperature, absolute pressure, foam quality, texture, foam-channel wall interactions, liquid phase properties, type and concentration of surfactant [9]. Therefore, the rheology of foams is more complex than that of other simple drilling fluids. However as contrary to the complexity of the rheological specification of foams as underbalanced drilling fluid, the ability to lift large quantities of produced liquids is most probably the main reason for its use.

2.2.1 Factors affecting rheology of foam

The rheology of foam is affected by certain factors. These factors include change in the quality, temperature and pressure variation and shear rate condition during the generation of foam.

2.2.1.1 Quality of foam

Foams are generally characterized according to their quality, which is defined as follows,

$$\Gamma = \frac{V_g}{V_g + V_l} 100 \tag{2.1}$$

where: V_g is the gas volume, V_l is the liquid volume and Γ is the foam quality, (%).

A number of rheological behaviors have been presented in the past for foam flow calculations. Beyer et al. [10] developed a model and concluded that foam is a complex mixture of gas and liquid whose rheological properties are influenced by the foam quality (ratio of gas volume to total foam volume). They investigated the independent variables affecting the flow behavior of aqueous foam and its liquid volume fraction. The viscosity and particle lifting ability of stable foam increase as liquid volume fraction decreases. They described the composition of the foam at any temperature and pressure by the Liquid Volume Fraction (LVF), which is

$$LVF(T,P) = \frac{VOL_L}{VOL_L + VOL_G + (T,P)} \tag{2.2}$$

where, VOL_L is the volume fraction of liquid phase in the foam and VOL_G is the volume fraction of gaseous phase in the foam.

Foam of high quality possesses less liquid than foam of low quality. The distribution of the bubbles and their size in the foam are described by its texture. Foam that is fine possesses smaller bubbles that are spherical while foam that is coarse possesses large bubbles that are polyhydric. According to these definition, sphere foam tends to be low quality while fine foam and polyhydric foam tends to be high quality [11]. The continuous liquid phase changes into a discontinuous situation when the foam quality is more than a specific threshold level; and results in formation of mist. The upper limit for stable foam has yet to be determined but it is most definitely a function of the rate of the shear. Beyer et al. [10] showed that the foam became unstable at liquid volume fractions of 0.02 to 0.03, and that when the quality exceeds 98%, the foam tends to flow as intermittent slugs of foam and gas.

Cawiezel and Niles [12] observed the influence of quality on the rheological properties of foam. According to them, the Herchel-Bulkley viscosity model can be used to describe the rheological behavior of foam fluid as it is a yield pseudo-plastic fluid. The conclusion was that the apparent viscosity of the foam increases as the quality of the foam increases.

Composition of the liquid phase with the gas phase is important for foam stability. Russell [13] observed that good bubble stability was generated by surfactant solutions at 99.1% quality of foam without polymer, known to be stable foam.

2.2.1.2 Effects of temperature and pressure

Beyer et al. [10] showed that foam is a complex mixture of gas and liquid whose rheological properties are influenced by the temperature and pressure.

$$\rho_F = \frac{PM}{PM(W_L SV_L + W_S SV_S) + W_G ZRT_1} \tag{2.3}$$

where,

$$W_G = \frac{m_g}{m_g + m_l + m_s} \tag{2.4}$$

$$W_L = \frac{m_l}{m_g + m_l + m_s} \tag{2.5}$$

$$W_S = \frac{m_S}{m_g + m_l + m_s} \tag{2.6}$$

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 liquid, W_S is the mass fraction of solid and Z is the gas compressibility factor. 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 bottom hole pressures when foam was pumped down a well.

Li and Kuru [8] reported that critical foam velocity is not influenced by temperature variation between $30°C$ and $100°C$ as shown in Figure 2.1 This conclusion is also supported by the experimental study of Loureno et al. [14]. They experimentally verified that rheology of foam was not disturbed by increasing temperature.

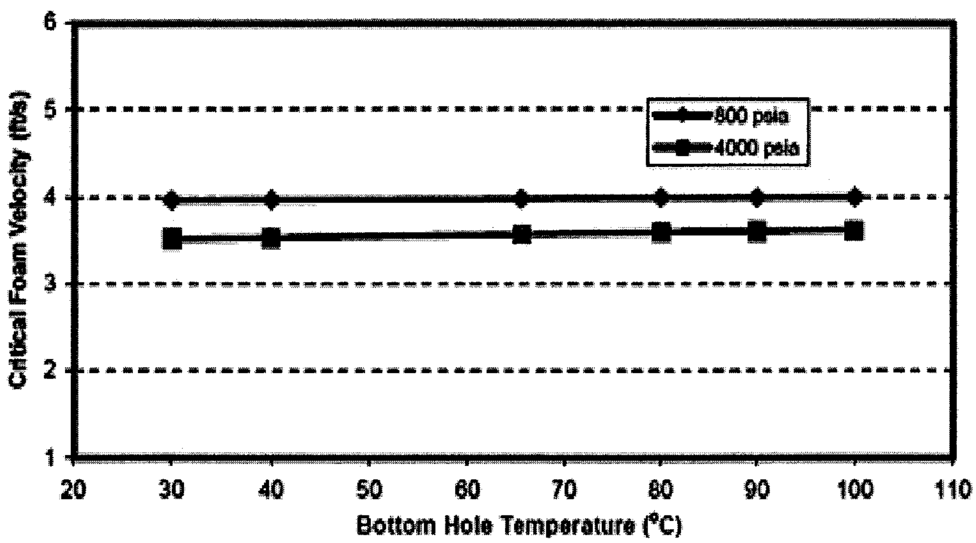

Figure 2.1: Effect of Bottom hole temperature on critical foam velocity [8]

Alexander and Ali [15] mentioned an example of the change in density, caused by temperature for a given wellbore conditions as shown in Figure 2.2. There is $14°C$ change in temperature after every 1000 ft increase in depth but the effect of temperature on the density of fluid can be controlled if the inlet fluid density is little bit higher than requirement. In case of deviated section of wellbore, temperature remains constant so no net change in density and viscosity in deviated section. Hence velocity of foam is significantly affected by variation of pressure along the wellbore.

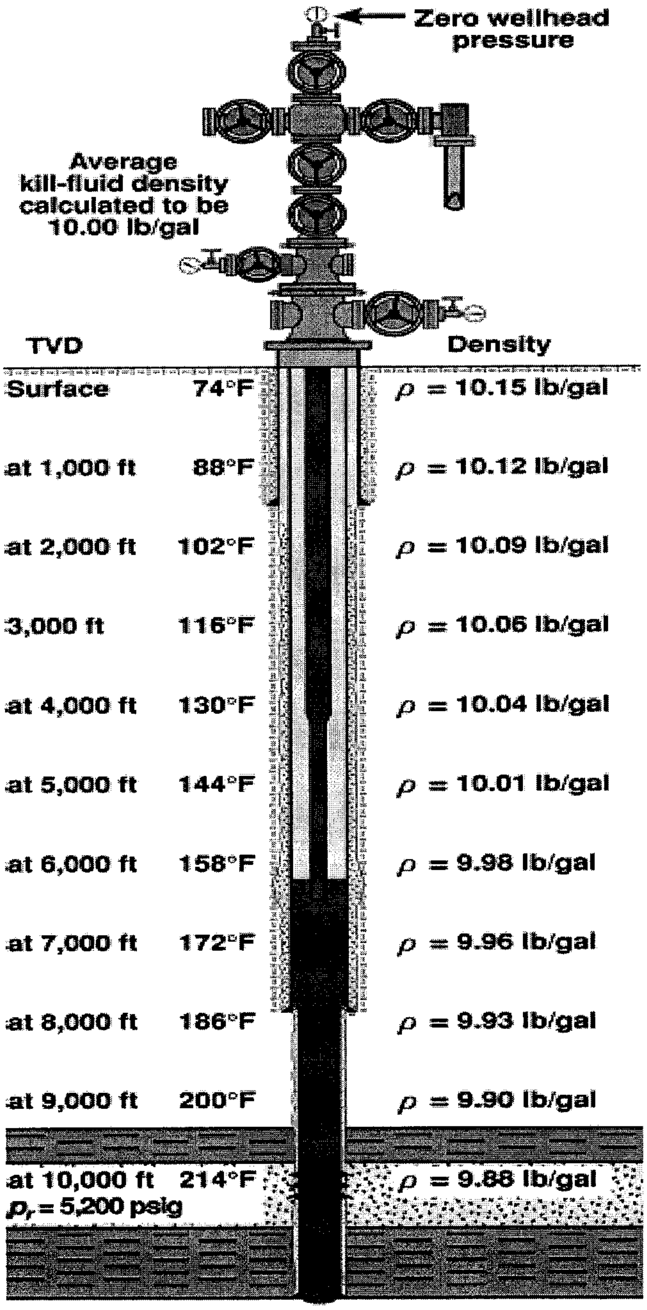

Figure 2.2: Effect of temperature on the fluid density [15]

2.2.1.3 Effect of shear rate

Lourenoet et al. [14] showed that foam generated at high shear rate condition has smallest bubbles and higher effective viscosities. They investigated the slippage at the wall and noticed that it is one of the most important phenomena to be considered in foam flow. Also, experimental result indicates a strong influence of texture on foam rheology while the effect of temperature and pressure is secondary.

2.2.2 Rheological relations of foam

The rheological behavior of foam has a vital role to play in the calculation of the solid transport efficiency. Over the past three decades, several rheological models have been proposed. Volume equalized principle was introduced by Valco and Economides [16] and the concept of the constant friction factor was its basis. The principle states that all data regarding the shear-stress/shear-rate during an isothermal experiment under varying geometries and qualities lie on a single curve if the shear-stress and shear-rates are both volume equalized. Volume Equalized models are written bellow;

Power Law Volume Equalized Model.

$$\tau = K_{VE}\varepsilon^{1-n}\gamma^{n} \tag{2.7}$$

Bingham Plastic Volume Equalized Model.

$$\tau = \tau_{y-VE^{\varepsilon}} + K_{VE}v_{VE}\gamma \tag{2.8}$$

Herschel Bulkley Volume Equalized Model.

$$\tau = \tau_{y-VE^{\varepsilon}} + K_{VE}\varepsilon^{1-n}\gamma^{n} \tag{2.9}$$

where, τ is the shear stress, K_{VE} is the consistency index, v is the velocity, γ is the shear rate, n is the power factor and ε is the specific volume expansion ratio.

It was reported by Saintpere et al. [17] that the Herschel-Bulkley model could give good indication of the efficiency of the foam-solid transport. They constructed a closed flow loop in order to determine rheological properties of foamed fluids. They concluded that apparent viscosity was a function of foam quality. Rheological behavior of foam was defined to be Herschel-Bulkley type. Higher quality foams produced higher shear stresses, and viscosities. At higher foam qualities apparent viscosity increased exponentially. They also concluded that viscosity of base liquid has directly effect on the viscosity of foam.

2.2.3 Friction pressure losses of foam

Blauer et al. [18] investigated the frictional losses in foam flow. Reynolds number can be predicted by using "effective foam viscosity", average foam annulus velocity, size of pipe, foam density. It was observed that friction losses for foam may be determined as for single phase fluid using conventional Reynolds number. They also concluded that foam behaves as a single phase Bingham plastic fluid.

For the prediction of frictional losses as a result of the solid phase in the solid-foam slurry flow a semi-empirical model has been presented by Okpobiri and Ikoku [19]. Moreover, Okpobiri built a theoretical model that was used for foam to predict pressure drops across the bit. A table that presented the dependence of the quality on the model parameters, K and n was developed. He used the "Volume Equalized Principle" that Valko and Economides [16] proposed. He believed that if an isothermal flow and alteration of the axial velocity on the radial velocity is negligible, then in short pieces of pipes, the foam's pressure gradient, temperature and density are constant; with this belief, he applied the formula, Haigen-Poiseuille, for the power law model.

The numerical results from Griffin and Lyons [20] and [21] are contradictory for the same well applying the same boundary conditions. There are many factors that affect the solid transport which include the property of fluid (rheology, friction, density, fluid losses, ease of disposal), well configuration (total vertical depth, bottom hole pressure, well size, tubing size, casing size, structure), operating conditions (flow rate and wiper trip speed) and the solid particles properties (density, average size, concentration and material type).

Medely et al. [22] presented a one dimensional steady state foam flow. They developed a new model that calculates varying friction factors along the circulation path. 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 solid particles concentration. Results are calculated with numerical methods. Inputs for the model are injection pressure, backpressure, gas and liquid injection rates. Friction factors are calculated by means of an improved version of Lord's [23] pressure drop equation and Sporker et al. [24] method. They developed a computer program to be used in the field. Gue et al. [25] developed a model to predict bottom hole pressure during underbalanced operation using foam. The model is based upon frictional and hydrostatic components. Their model can be used for both vertical and inclined wells. Buslov et al. [26] used iterative procedure to find the pressure losses in annulus foam flow.

Ozbayoglu et al. [27] measured foam pressure loss across a 90-ft horizontal pipe. On the basis of experimental data and the results of the model, they concluded that there is no best model for predicting the pressure losses during foam flow in pipes. Their model was not able to predict pressure losses consistently. However, their model gives an overall better result for 90% foam quality.

2.2.4 Annular foam velocity for vertical well cleanup

The foam-temperature, velocity, pressure, density and quality distribution in the vertical wellbore was investigated by Li et al. [3]. Compulsory analyses of these factors had to be performed for the hydraulic calculations of the flow of the foam. It was shown that for the case of a vertical well, in order to achieve a successful cleaning, the velocity of the foam fluid should be in accordance with the equation that as follows.

$$V_F \geq 1.1 V_t \tag{2.8}$$

$$V_t = \left[\frac{g D_S^{n+1}}{18K(1.02431 + 1.44798n - 1.47229n^2)} (\rho_S - \rho_F) \right]^{\frac{1}{n}} \tag{2.9}$$

where, V_t is the terminal velocity, D_S is the diameter of the particle of sand, is the sand's density, ρ_F is the foam's density and n is the exponent.

2.3 Numerical study of cuttings transport

There are many numerical studies conducted in relationship with application of computational fluid dynamics (CFD) to estimate pressure drop and cuttings concentration.

A new technique was presented by Bilgesu et al. [28] to determine the factors affecting the transport of cuttings in wellbores. They used computational fluid dynamics (CFD) software to determine the efficient transport of cuttings in both horizontal and vertical wellbores. The size of the cuttings and the mud density were the influencing factors used. The factors were changed around in the simulation and it was observed that the annular velocity performed a vital role in hole cleaning. Moreover, there was a more pronounced increase in the efficiency of the transport of the cuttings at flow rates that were low. A comparison of the reported data with the results was made; it was found that the results were in good agreement. However, the prediction from the model was off a bit in regards to the data from the laboratory as there was an increase in the annular velocity for all of the densities of the mud because of the particle sizes varying.

Jain et al. [29] studied the effect of coil tubing curvature on the pressure drop of both Newtonian and non-Newtonian fluids. They studied the pressure drop for water in $1\frac{1}{2}''$ and $2\frac{3}{8}''$ tubing with reel diameter of $72''$, as shown in Figure 2.3 and Figure 2.4. They investigated that coiled tubing has huge secondary flow effects which lead to higher pressure losses of the fluids. It was noticed that there was an increase in pressure drop with the increase of curvature ratio of coil. It was recorded that change in the curvature ratio to the order of 0.002 has no considerable effect on the pressure drop. It was concluded that curvature effects on pressure drop are more prominent for non-Newtonian fluid as compared to Newtonian fluids.

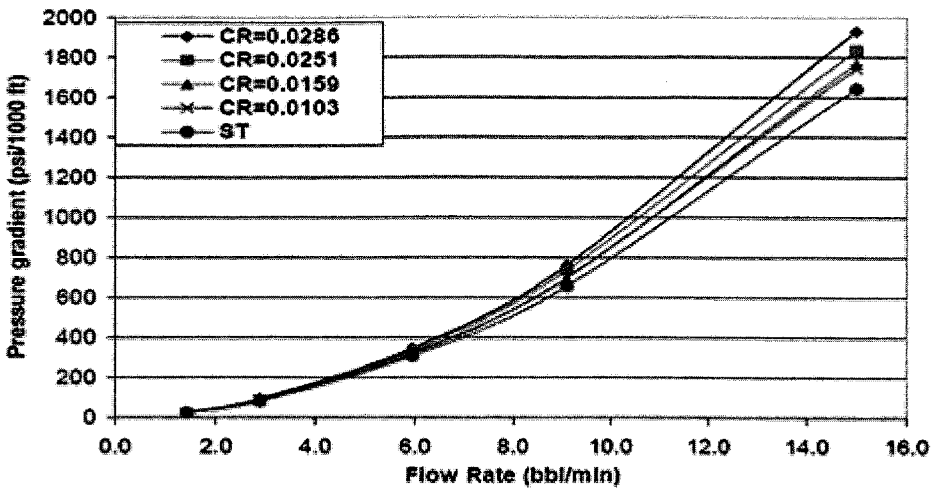

Figure 2.3: Simulated frictional pressure gradient of water in $1\frac{1}{2}''$ tubing for different curvature rations [29]

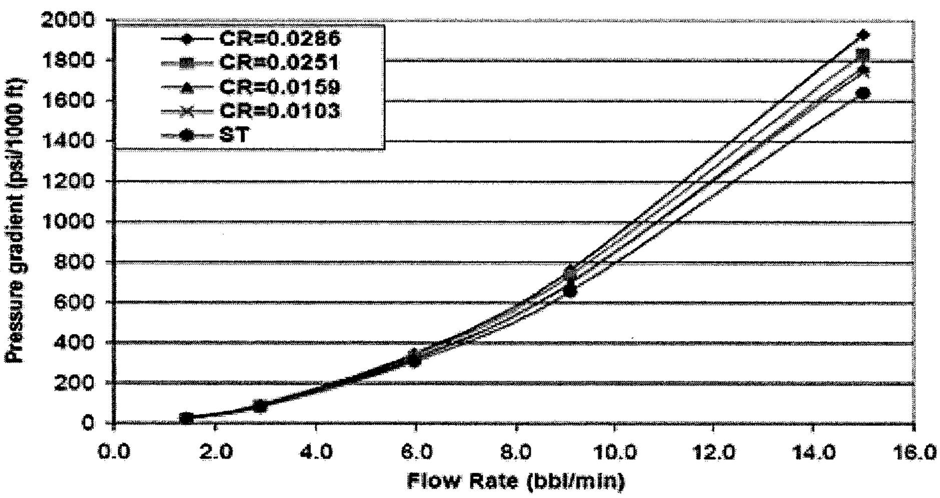

Figure 2.4: Simulated frictional pressure gradient of water in $2\frac{3}{8}''$ tubing for different curvature rations [29]

The flow behavior and losses of frictional pressure in both Newtonian and Non-Newtonian fluids in concentric annulus was studied by Singhal et al. [30]. In that study, the CFD software program was used to simulate annular flows for both turbulent and laminar regimes. Jones was shown to have the best correlation for the Newtonian fluid in the laminar flow system and Drew was shown to have the best correlation in the turbulence flow system. A comparison was carried out between the results and the experimental data and the correlation for the Newtonian and Non-Newtonian fluids which were available and good agreement was found.

Ozbayglu and Omurlu [31] studied the effect of eccentricity on the flow of non Newtonian fluid using the Finite Element Method. A $5\frac{1}{2}''$ wellbore with fully concentric, 50% eccentric and eccentric cases for flow rates from 50 to 200 gpm for three different mud densities is used. They investigated that as the eccentricity increase, friction losses decreases. They accurately calculated the frictional pressure losses for eccentric and concentric cases. Pressure drop for different positions of inner tubing inside the annulus is shown in Figure 2.5

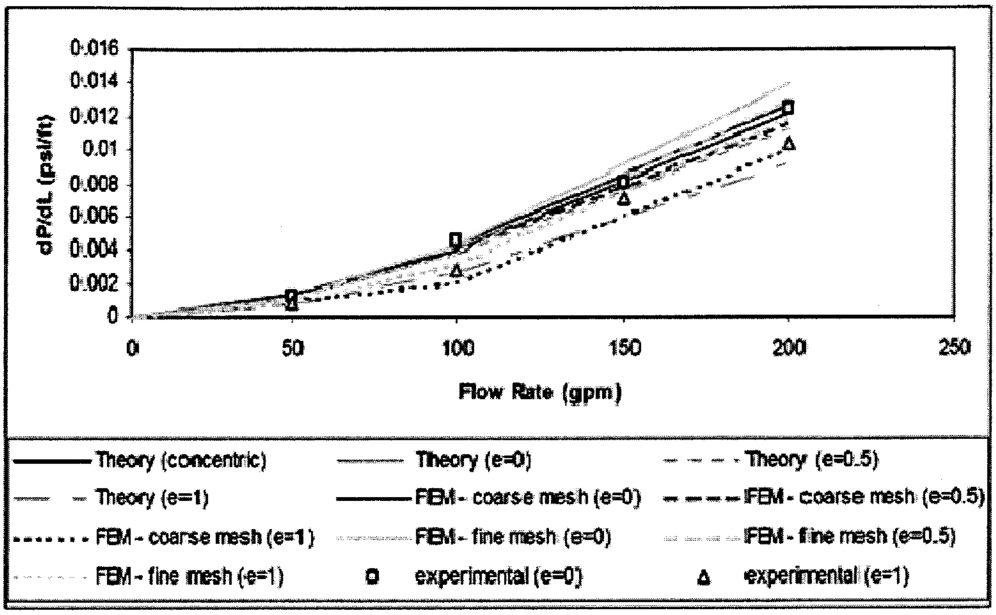

Figure 2.5: Friction pressure loss comparison [31]

Bailey et al. [32] simulated the fluid flow of non Newtonian slurry composed of gel and sand at reel to injector section of coil tubing unit. The gel was 40 lb/gal and sand concentration is taken as 8 lb/gal, which was uniformly distributed at the inlet. They predicted that pressure gradient remained consistent and produce linear results. The change in curvature of coil tubing reel has no effect on pressure drop. The pressure drop from each wrap of tubing remained linear for given reel diameter. Figure 2.6 is showing the pressure drop for $2\frac{3}{8}''$ tubing.

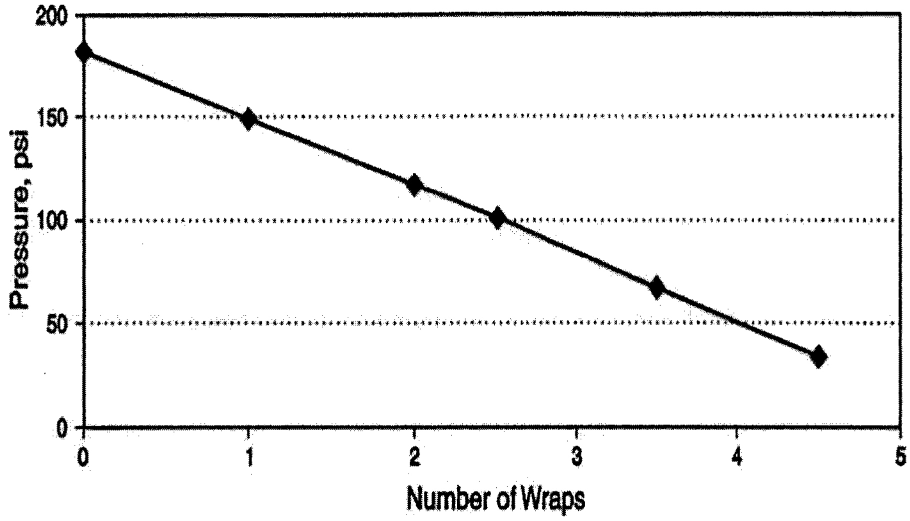

Figure 2.6: Pressure gradient per wrap in $2\frac{3}{8}$" tubing [32]

The study by Dongping and Samuel [33] was focused on determining the impact of a standoff device on the calculation of the pressure drop and the circulating density of the down hole. The computational fluid dynamic software was used for the analysis of the standoff devices and the calculation of the pressure drop was performed using the Navier-Stoke equations. As a result, Dongping and Samuel [33] were able to build a model with which the prediction of the pressure drop with the standoff devices demonstrated improvement. The conclusion was that the equation could be utilized for stabilizers and other devices.

2.4 Factors affecting cutting transport with foam

In the past many studies were carried out to investigate the cutting transport with foam. There are many factors which affect the cuttings transport. Cuttings transported through the annulus in deviated wellbore are affected by a many factors. The study of these factors was carried out by several investigators over the decades. According to these investigators, the factors affecting cuttings transport in the wellbore can be described as follows:

2.4.1 Effect of annular velocity (flow rate)

Millhone et al. [34] concluded that fill lifting increases with increasing gas rate. Their result showed that in larger wells, lift decreases as liquid rate increases. Okpobiri and Ikoku [35] determined a procedure using iterative scheme to find the minimum velocity of foam to clean out the well. They assumed the annulus flow as a homogenous mixture of solid particles and foam. Increase in mean annular velocity results in an increase in effective particle settling velocity in non-Newtonian fluids [36]. High annular velocity for more viscous fluids do not effectively increase transport ratio but results in greater parasitic losses and washout [37].

Osunde and Kuru [38] studied the effect of varying gas and liquid injection rate on the solid particle transport. Figure 2.7 has illustrated the effect of gas injection effect on cutting transport. It was investigated that gas flow rate has prominent effect on the solid particles transport. They noticed that cutting concentration dramatically reduced with the increase of gas injection. Increase in gas flow rate means that quality of foam is increasing. As the quality of foam increases which improves the viscosity of foam so lift ability of foam increase with high flow rate of gas.

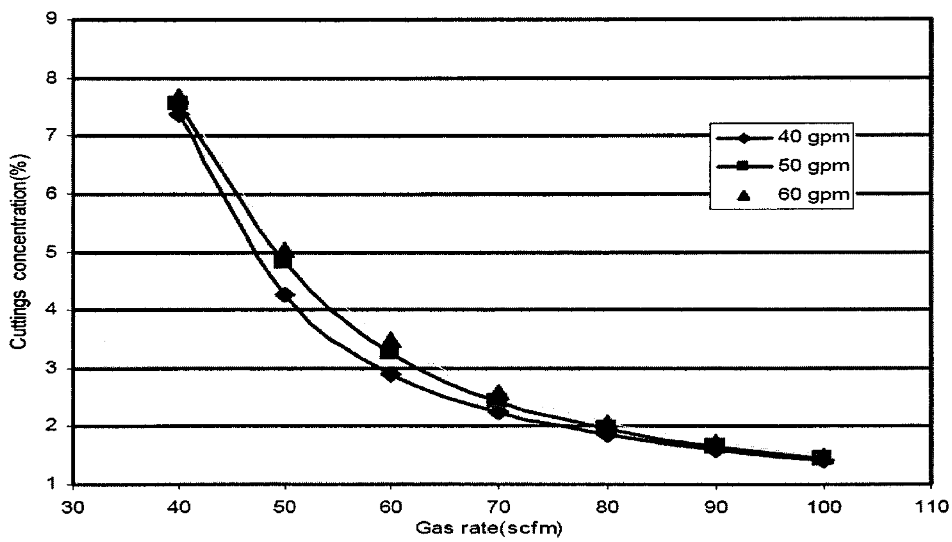

Figure 2.7: Effect of varying gas and liquid injection rate on cutting concentration [38]

Li and Walker [39] experimentally examined the effect of different parameters for hole cleaning in directional wells. They studied the effects of gas-liquid ratio, flow rate, phase slip velocities and fluid properties on cuttings bed thickness for aerated fluids systems. They observed that liquid is the dominating parameter for cuttings transport in aerated systems. As the liquid ratio increases, for a constant in-situ flow rate, cuttings transport improves as shown in Figure 2.8.

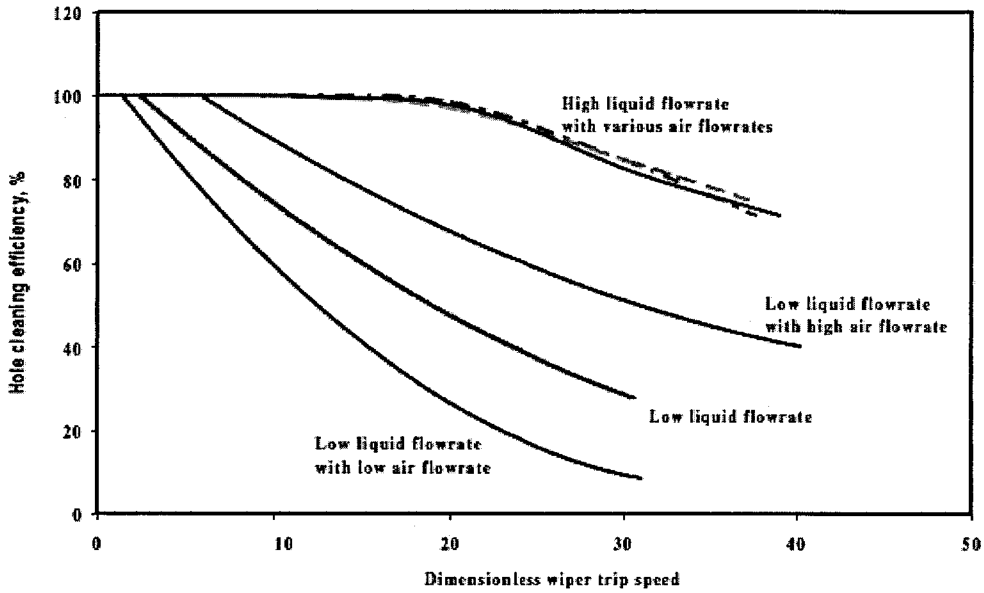

Figure 2.8: Effect of the addition of the gas phase on the hole cleaning efficiency for water at 90 degree [39]

Li and Kuru [40] developed a model of solid transport with foam in horizontal well. They introduced a new critical velocity correlation for foam solid particles flow. Improved fill transport efficiency with increasing foam flow rate suggested that as long as the equivalent circulating foam density stays below the required limit for low formation pressure, maximum possible gas/liquid injection rate should be used for effective well cleaning. They investigated that cuttings bed height decreases with the increase of flow rate of foam as shown in Figure 2.9.

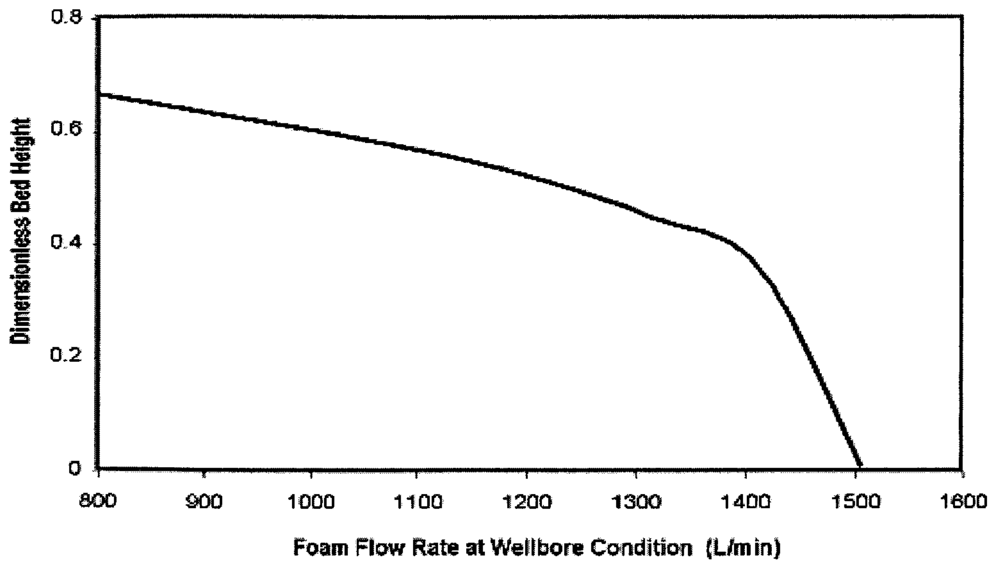

Figure 2.9: Effect of foam flow rate on cutting bed height [40]

Experiments were performed by Zhou [41] at various gas and liquid flow rates as well as raised temperatures in a unique full-scale flow loop. A specially designed multiphase measurement system was used to determine the concentration of the in-situ cuttings. It is obvious from the results that the efficiency of the transport of the cuttings and the associated drop in the frictional pressure are affected by not only the flow rate of a liquid and the ratio of gas to liquid but the temperature also has a significant affect. The volume of the cuttings amassed in the annulus showed a strong sensitivity to the rate of the liquid flow. A mechanistic model for transport with aerated fluids of the cuttings under EPET conditions has also been developed in this study; it was developed for prediction of frictional pressure loss and the concentration of the cuttings in the annulus. Higher flow rates clean larger particles better [42].

2.4.2 Effect of drillpipe eccentricity

Li and Kuru [40] studied the effect of eccentricity on cutting transport with foam. They predicted that cuttings bed height depends on the position of drillpipe (pipe eccentricity). They noticed the highest cutting transport when inner pipe was fully concentric as shown in Figure 2.10 which cannot be achieved practically in the deviated wells.

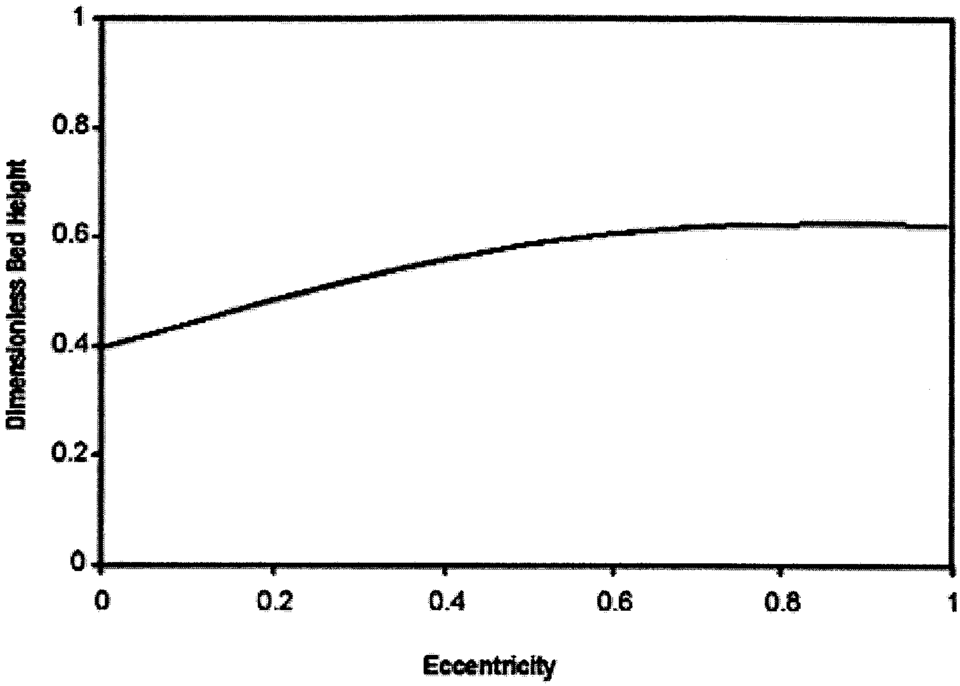

Figure 2.10: Effect of drillpipe eccentricity on cutting bed height [40]

2.4.3 Effect of cuttings size

Particles with thickness to diameter ratio less than 0.3 are hard to transport from the wellbore, unless fluid is maintained in turbulent flow [43]. Small and medium cuttings sizes are better transported at high annular velocity [37] and [28]. Larger cuttings sizes are better transported in high viscous fluids than low viscous fluids [44].

Walker and Li [45] presented the particle size and fluid rheology effects on cutting transport. They recommended that fluid must have maximum carrying capacity so multiphase system should be used for solid transport from deviated wellbore. They investigated that fine particles are easiest to clean out but the particle with an average size of 0.76 mm are difficult to remove.

2.4.4 Effect of foam quality

The solid carrying capacity of foam was investigated experimentally by Herzhaft et al. [46]. They concluded that the particle carrying transport efficiency was increased with an increase of the quality of the foam. Li and Kuru [40] studied that higher foam quality causes a decrease in the cuttings bed. Their investigation showed that cuttings bed height decreases as the foam quality increases as shown in Figure 2.11. Enhancement in the cutting transport was noticed due to increase in the effective viscosity of the foam.

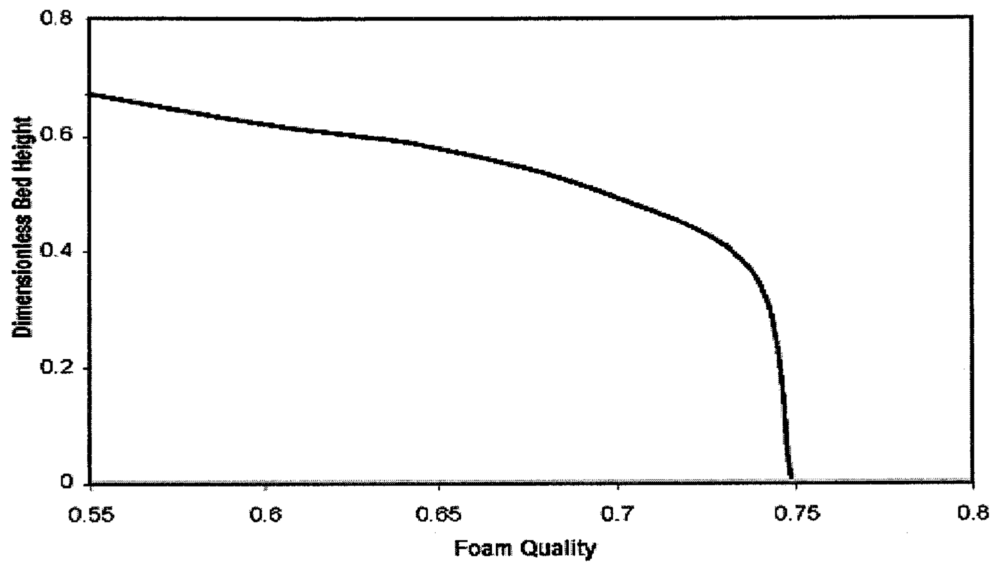

Figure 2.11: Effect of foam quality on cuttings bed height [40]

Capo et al. [47] conducted test to determine the effect of inclination, foam quality, foam velocity and rate of penetration on solid particle transport. Their tests showed that transport of solid particles has better performance with foam of low quality due to higher mass flow rate of foam.

Chen et al. [48]. showed that the transport of solid particles has a better performance with foam of low quality because of high mass flow rate. They predicted that under elevated temperature and pressure, there are slightly change in the solid removal capability but the changes are limited. This shows that foam sustains its solid removal properties well even under elevated conditions. Figure 2.12 shows the pressure drop. They observed that adding the viscous polymer improves the solid removal but increase frictional pressure loss. They further observed the fact that frictional pressure losses in the annulus are moderate when solid particles are injected in the foam, because the flow is predominantly laminar. Figure 2.13 shows the removal rate of cuttings, they predicted that volume of solid particles accumulated in the annulus is not sensitive to flow velocity increase until critical velocity is achieved and the well is cleaned. The critical velocity of 90% is approximately 6ft/s.

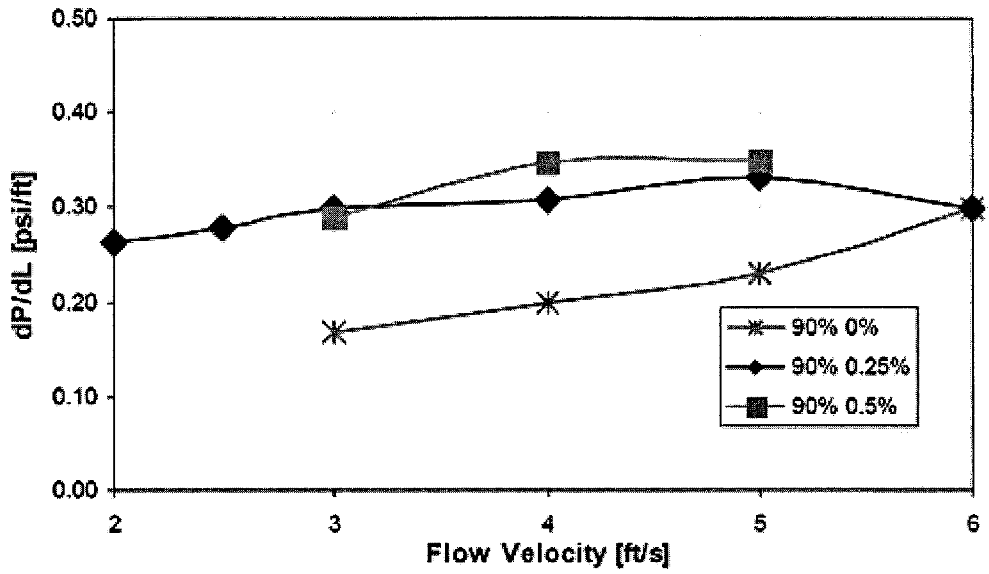

Figure 2.12: Annular pressure gradient vs. flow velocity of 90% quality foam [48]

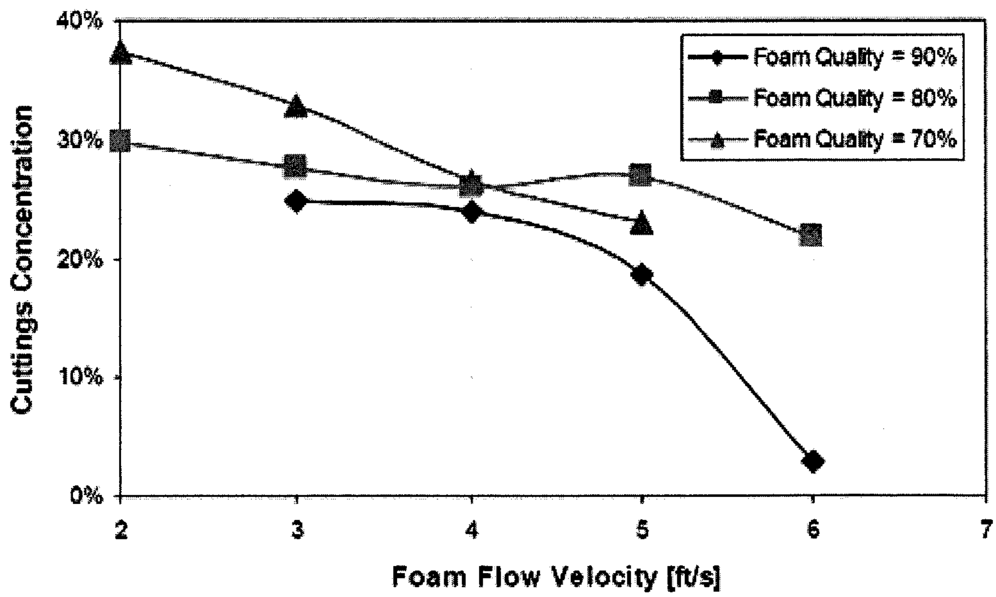

Figure 2.13: Cuttings concentration vs. flow velocity for aqueous foam, Quality: 70, 80 and 90% [48]

2.4.5 Effect of drillpipe rotation

Drillpipe rotation rapidly removes cuttings in muds of high viscosity and high gel strength by creating turbulence [43]. Drillpipe rotation creates additional tangential flow to the axial flow which results in large increase in particle recovery fraction [36]. Hole cleaning is highly enhanced with drillpipe rotation during circulation [49]. Increase in drillpipe rotation from zero measurably increases the average particle rise velocity [50], [51] and [52]. Increase in drillpipe rotation increases the shear rate and annular point velocity near the drillpipe [53]. Effective viscosity of drilling fluid increases as drillpipe rotation speed increases [52].

2.4.6 Effect of rate of penetration (ROP)

Li and Kuru [40] studied that cuttings deposition increases as the rate of penetration of drillpipe increases with foam fluid as shown in Figure 2.14 This analysis is helpful to determine the required drilling rates for the given wellbore geometry and foam flow rate to minimize the settlement of cutting particles.

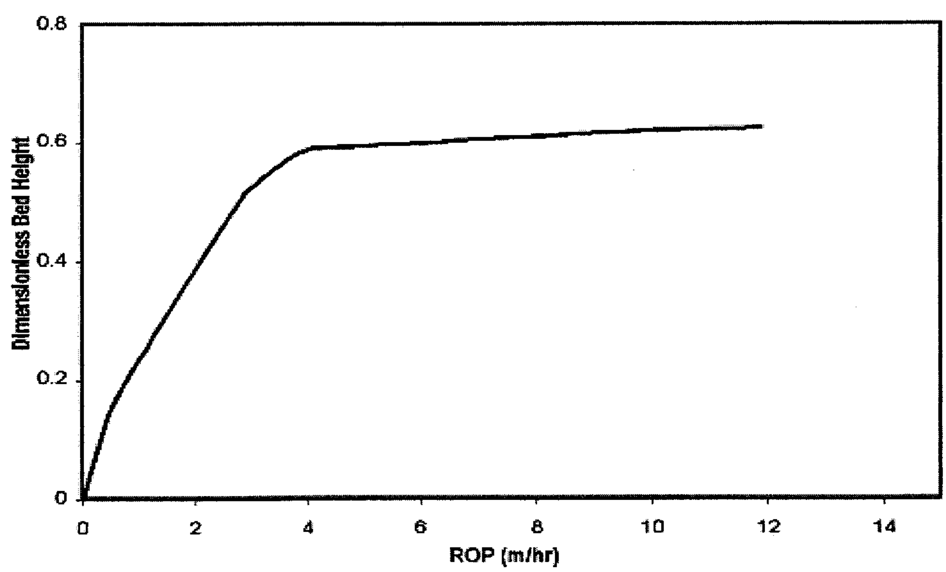

Figure 2.14: Effect of drilling rate on cutting bed height [40]

2.4.7 Effect of wiper trip

Walker and Li [54] used the previous flow loop setup and simulated the wiper trip hole cleaning. 'Wiper Trip' is defined as in and out movement of tubing inside hole. They estimated the rate of removal of fines, cuttings and sand as shown in Figure 2.15. They observed that with the wiper trip cleaning, the addition of gas phase up to 50% gas volume fraction, maximum cleanout effectiveness is up to 10-20%. For example, if the well was 80% cleaned out with water in the wiper trip hole cleaning mode, with the addition of gas fraction ,the solid transport efficiency can be increased to 85%. Even though with stationary hole cleaning there is dramatic increase in hole cleaning with addition of gas phase. The addition of gas phase is beneficial in low pressure reservoirs and where there are limitations due to hydrostatic conditions.

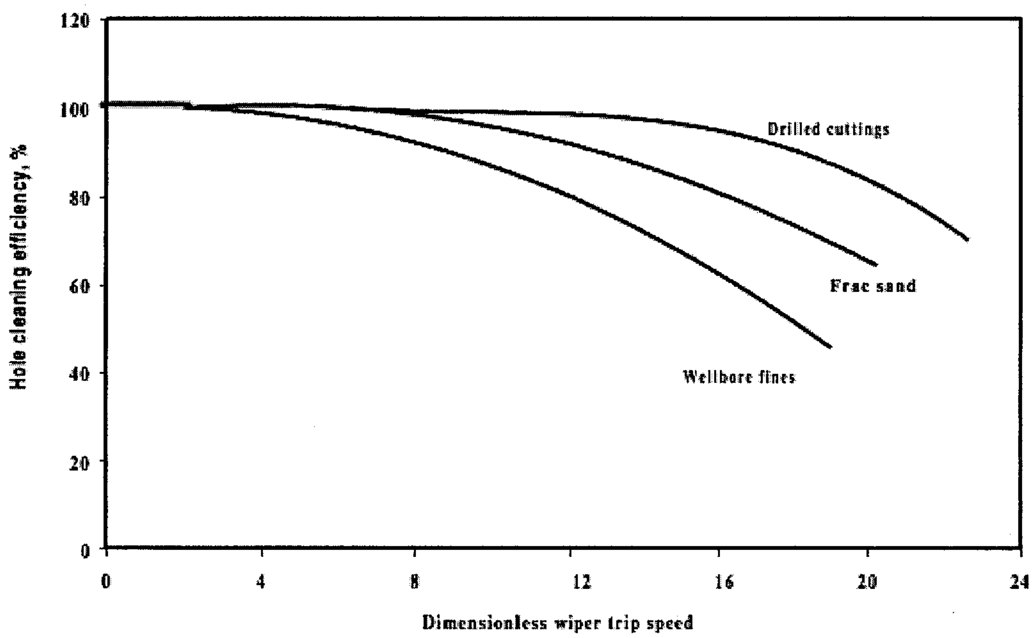

Figure 2.15: Effect of particle size on the hole cleaning efficiency with water at 90 degree [54]

2.4.8 Effect of inclination

Martin et al. [49] observed the effect of inclination in wellbore cleaning. They concluded that effect of inclination is apparent as soon as the well deviation angle is greater than 10° from vertical and removal of solid particles becomes difficult between 30° and 90°. They noted that high viscosity of the operating fluid is quite favorable for cleaning at vertical section, but its ability to lift decline in deviated region. Guo et al. [25] presented a model to find bottom hole pressure through the pressure dependent fluid density. An empirical model was presented by Martins et al. [55] that could predict the height of the fill bed during the time the foam was flowing into inclined and horizontal wells.

As presented by Clark and Bickham [56], the wellbore angle is the greatest factor influencing the transport of cuttings to the surface from the drill bit. It was observed, in this study, that for high angles, where formation of a stationary cutting bed can take place, transport is achieved by way of a rolling mechanism. The mechanism where the formation of a churning and moving bed can take place at intermediate angles is known as lifting. Transport is determined by particle settling at angles close to vertical.

Osunde and Kuru [38] predicted that cutting concentration become high with the increase of inclination angle from vertical for same liquid and gas injection rate as shown in Figure 2.16.

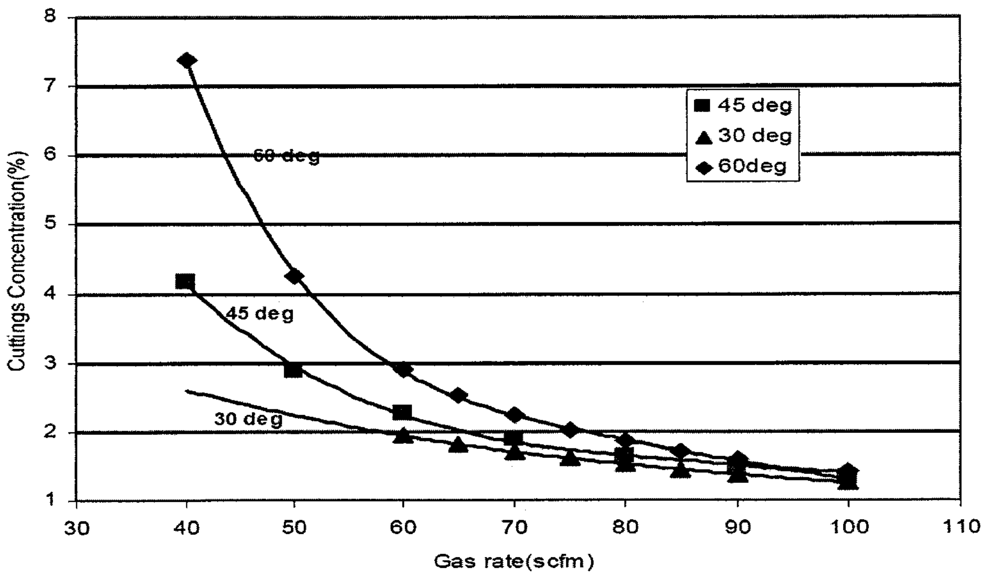

Figure 2.16: Effect of inclination on cuttings concentration [38]

2.4.9 Effects of foam density and viscosity

Foams can have high viscosity values, a value that is greater than both constituents, for a constant shear rate. However, foam has a density lower than that of liquid phase. Their high viscosity allows efficient cuttings transport and low density allows underbalanced conditions to be established. Drilling with foam has shown increased productivity, increased drilling rate, and reduced operation troubles such as lost circulation, differential stuck pipe, and gives improved formation evaluation while drilling [27]. Although drilling with foam is very valuable due to its very low density coupled to its excellent cuttings carrying ability, characterization of foam properties under drilling conditions is still incomplete and this could be an obstacle to the use of this technique by operators [46].

2.5 Concluding remarks

Reviewed research showed that the foam-solid transport study is very important to understand the well cleanup operation with coiled tubing. It would be cost efficient because, currently nitrogen is being used to clean the wells which have underbalanced conditions. In the past foam rheology has been discussed in detail. It can be concluded that foam has high viscosity which is required to suspend the particles even at low annular velocities.

There are several researches done about the rheology of foam and many studies are present about cuttings transport with foam during drilling operation. Effect of eccentricity, ROP, gas and liquid injection rate, particle size, pipe rotation, well inclination and foam quality have been studied in the past to understand the cuttings transport with foam.

Foam is an intricate mixture of a gas, a liquid and a surfactant. The rheological properties of foam are significantly affected by factors, such as, absolute pressure, temperature, texture, foam quality, foam-channel wall interactions and the characteristics of the liquid phase as well as the kind of surfactant used and its concentration. The rheology of foams, therefore, is more intricate than the rheology of other simple drilling fluids. However, contrary to the rheological specification of foams as underbalanced drilling fluids being complex, the main reason for using foam is most likely related to its capability of lifting large amounts of produced liquids. Solid particles can also be removed successfully by foam.

They have also been utilized in depleted reservoirs when working-over wells. This is due to their successes as a property of medium insulation when there is a problem of circulation loss. Several rheological behaviors have been suggested for calculating the flow of foam, most of the studies showed that water based foam follows Herchel-Bulkley viscosity model.

Study is found for vertical wellbore cleaning with foam. There is a need of analysis to find out the annular velocity and quality of foam to clean up the horizontal wellbore. There is also need to predict the pressure drop at different qualities of foam during coil tubing cleanup operation.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discusses the detail procedure of the numerical model. ANSYS-CFX-14 has been used to simulate the two phase flow in the horizontal section of a wellbore considering the effect of influencing parameters such as particle size, fluid velocity, quality and diameter ratio at cleanup operation. As a result, flow pattern, fill concentration and pressure drop is identified along the annulus. In order to develop the numerical model for fill transport, the following steps are adopted as indicated in Figure 3.1.

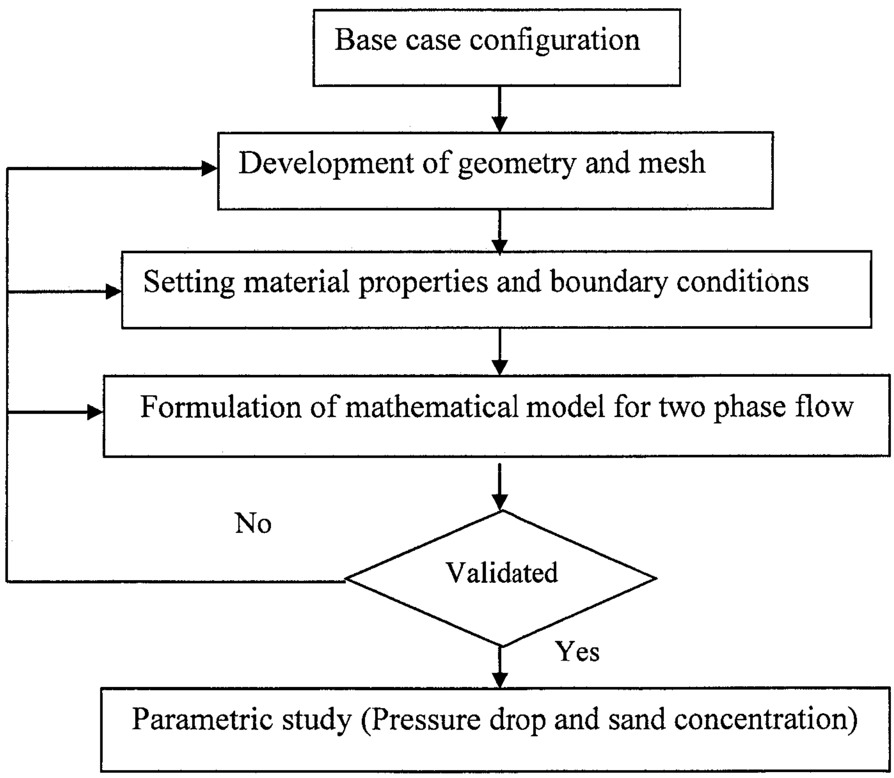

Figure 3.1: Procedure for Numerical model

3.2 Assumptions to set up the model

The following assumptions are made for the development of foam-solid flow model in the horizontal wells:

- Foam is considered as homogenous and non-Newtonian fluid whose rheological property can be presented by a Herschel-Buckley viscosity model
- Foam flow is isothermal in the horizontal annulus and steady state
- Particles shape is spherical and uniform size
- Particle velocity is uniform at any cross section of the well
- Injection of particles is uniform at the annulus inlet
- Rate of penetration of tubing is constant i.e. 60-ft/hr
- Tubing is concentric in the wellbore, also inner wall of casing and outer wall of tubing is smooth i.e. there is no roughness

3.3 Governing equations

The main equations governing for estimation of pressure drop and cuttings concentration in ANSYS CFX 14 are equation of continuity which is used for calculation of mass transfer of solid-liquid flow and equation of momentum used for observing the motion of solid particles in the foam. Following are the momentum equations for foam flow:

$$\frac{\partial(\rho_f u_f)}{\partial t} + \nabla.(\rho_f u_f V) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \tag{3.1}$$

$$\frac{\partial(\rho_f u_f)}{\partial t} + \nabla.(\rho_f v_f V) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \tag{3.2}$$

$$\frac{\partial(\rho_f u_f)}{\partial t} + \nabla.(\rho_f w_f V) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \tag{3.3}$$

Continuity and momentum equations for solid particle phase are as follow:

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla.(\alpha_p \rho_p \overrightarrow{u_p}) = \dot{m}_{fp} \tag{3.4}$$

$$\frac{\partial}{\partial t}(\alpha_p \rho_p \vec{u}_p) + \nabla.(\alpha_p \rho_p \vec{u}_p \vec{u}_p) = -\alpha_p \nabla.p_f + \nabla.\bar{\tau}_p + M + \vec{F}_p \tag{3.5}$$

where, f and p represent the foam and particle phase, α is the volume fraction, ρ is the density, $\alpha_p \nabla p_f$ is the foam pressure, $\nabla.\overline{\tau_p}$ is the solid stress tensor, M is the phase interaction term, $\overrightarrow{F_p}$ is the interfacial force, $\overrightarrow{u_p}$ is the solid particle velocity and $\dot{m}_{fp}$ is the mass transfer. Interfacial momentum transfer models M is as follow:

$$M = \sum_{\beta \neq \alpha} M_{\alpha\beta} \tag{3.6}$$

As the interfacial forces between foam and particle is equal and opposite so net interfacial forces sum to zero:

$$(M_{\alpha\beta} = -M_{\beta\alpha}) \Rightarrow \sum_{\alpha} M_{\alpha} = 0 \tag{3.7}$$

The total interfacial forces acting between foam and solid phases arises from several other forces:

$$M_{\alpha\beta} = M_{\alpha\beta}^{D} + M_{\alpha\beta}^{P} + M_{S} + \ldots \tag{3.8}$$

The forces indicated above respectively shows the inter phase drag force, pressure gradient and solid pressure force.

3.4 Equation of motion and forces acting on the particle

For the modeling of particle-liquid flows, there are two general approaches. One is the Eulerian approach. In this method, the particles are treated as a continuous phase and the motion of the particulate phase is mathematically described by conservation equations. The second one is Lagrangian approach usually known as a "trajectory model", where the momentaneous motion of equations of motion of an individual particle is tracked. The Eulerian approach is more appropriate if the two phases are weakly coupled or the dynamic interaction between the two phases is important whereas Lagrangian approach is more suitable for other situations. Between the two approaches, the Lagrangian one appears to be more suitable and reliable to deal with such complicated situations. Therefore in this study, the motion of particles in fluids is described in a Lagrangian way. To analyze the fill transport in the foam, discrete fill particles were introduced in continuous foam domain. The forces experienced by fill particles are affected by the acceleration due to the difference in the velocity between foam and fill particles.

The general form of momentum equation to describe a particle motion in a liquid flow are as follow:

$$m_p \frac{du_p}{dt} = F_D + F_B + F_R + F_P - F_G \tag{3.9}$$

$$m_p = \rho_p \frac{\pi D_p^3}{6} \tag{3.10}$$

where m_p is the mass of the solid particle, dUp/dt is the particle velocity and left hand side show the forces that affected on the particles motion. The forces which act on the particle are drag force (F_d), buoyancy force (F_b), rotational force (F_r), pressure gradient force (F_p) and external force. The interaction between these forces affects the solid particle transport during fluid circulation which is shown in Figure 3.2.

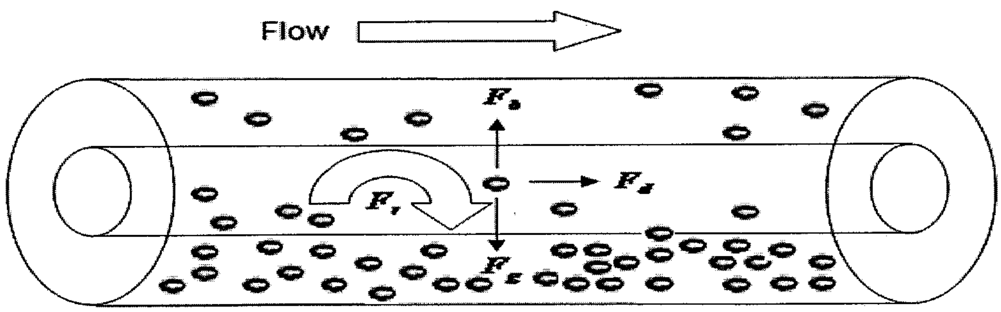

Figure 3.2: Interaction of forces acting on flowing particle

3.4.1 Drag force acting on the particle

In the calculation of all the forces, many fluid variables, such as density, viscosity, and velocity are needed at the position of the particle. When the surrounding foam moves relative to a solid particle, an additional force is exerted from the foam onto the submerged particle. The drag force, F_D, acts in the direction of the slip velocity $(v_s = v_f - v_p)$ between the liquid and the solid particle. Drag forces acting on the particles are defined as follow:

$$F_D = \frac{1}{2} C_D \rho_f A_p |v_f - v_p| (v_f - v_p) \tag{3.11}$$

For spherical particle and in terms of slip velocity

$$F_D = \frac{1}{2} C_D \rho_f \frac{\pi D_p^2}{8} |\vec{v_s}| \vec{v_s} \tag{3.12}$$

where, F_d is the drag force, C_D is the drag coefficient, A_p is the affective fill particle cross section and v_s is the slip velocity, v_f is the foam velocity and v_p is the particle velocity.

The drag coefficient in Equation (3.12) is highly dependent on the fluid regimes of laminar and turbulent. For laminar regime, Stokes (1851) solved the fluid dynamics equation for flow past a sphere, determining the drag force in the sphere as

$$\vec{F_D} = 3 \rho_f \mu_f (\vec{v_f} - \vec{v_p}) d_p \tag{3.13}$$

where, drag coefficient is defined as follow

$$C_D = \frac{24}{\rho_f (v_f - v_p) d_p / \mu_f} \quad \text{when Re} < 1 \text{ (stokes regime)} \tag{3.14}$$

where, μ_f is the fluid viscosity

3.4.2 Absolute pressure and buoyancy force

To calculate buoyancy, the following source term is added to the momentum equation:

$$S_{M,bouy} = (\rho - \rho_{ref})g \tag{3.15}$$

In the numerical setup buoyancy was activated, so pressure in the momentum equation excludes the hydrostatic gradient due to ρ_{ref} thus the pressure relates to absolute pressure:

$$P_{abs} = p - p_{ref} + \rho_{ref}\vec{g}(\vec{r} - \vec{r}_{ref})g \tag{3.16}$$

where, $\overrightarrow{r_{ref}}$ is the reference location. The buoyancy reference location option is set along the bottom side of the wellbore in the CFX-pre. This absolute pressure is used to calculate the pressure drop in the annulus. Each particle experiences the buoyancy force according to following equation:

$$F_B = (m_p - m_f)g = m_p(1 - \frac{\rho_f}{\rho_p})g = \frac{\pi}{6}d_p^3(\rho_p - \rho_f)g \tag{3.17}$$

where, m_p is the mass of particle, m_f is the mass of foam, ρ_f is the density of foam, ρ_p is the density of particle, g is the gravity vector and d_p is the particle diameter. As gravitational force overcome the buoyancy force so settlement of particles occurs along the bottom side of wellbore.

3.4.3 Pressure gradient force

The pressure gradient force results from the foam pressure gradient around the fill particles and is defined as follow.

$$F_P = -\frac{m_f}{\rho_f}\nabla p \tag{3.18}$$

$$\nabla p = \left(\frac{\partial p}{\partial x} + \frac{\partial p}{\partial y} + \frac{\partial p}{\partial z} \right) \quad (3.19)$$

where, m_f is the mass of the foam and ρ_f is the density of the foam.

3.4.4 Rotational force

Present numerical model was validated with experimental data of foam-cutting transport, so inner pipe rotation is involved in the experimental flow loop test. In the present study, rotational force is involved to validate the numerical model with experimental data. As model is validated with flow loop of foam-cutting transport in which inner pipe rotation is involved, so, the effect of rotational force on the particle transport is also introduced by considering rotational force. The rotational force causes the rotation of fluid domain which helps in the suspension of the solid particles. Therefore, less concentration of particles was identified with the introduction of rotational force. The flow of foam-solid mixture is in the rotating frame of reference, which is rotating at constant angular velocity ω , additional momentum sources are required to calculate the effect of angular acceleration which is the sum of centripetal and coriolis forces:

$$S_{M,rot} = S_{cfg} + S_{cor} \quad (3.20)$$

$$S_{cor} = -2\rho\omega \times U \quad (3.21)$$

$$S_{cfg} = -\rho\omega \times (\omega \times r) \quad (3.22)$$

where, U is the relative frame velocity and r is the location vector.

3.4.5 Gravitational force

The body force due to gravitational acceleration is determined from the solid particle volume and density. The gravitational force on a spherical solid particle is

$$\overline{F_G} = \frac{1}{6}\pi d_p^3 \rho_f g \quad (3.23)$$

where, g is the gravitational acceleration

3.5 Parameters and boundaries

The horizontal concentric wellbore model is developed according to the experimental flow loop by Chen et al. [48]. Table 3.1 shows the well dimensions and input parameters used in the validation and present study.

Table 3.1: Well dimension and parameters

Parameters	**Validation**	**Present study**
Wellbore Length (ft)	73	90
Outer pipe diameter (inch)	5.76	7.8
Inner pipe diameter (inch)	3.5	2.75, 3.15, 3.54, 3.93
Solid particle diameter (mm)	3	0.5, 1, 2, 3
Foam qualities (%)	70, 80, 90	70, 80, 90

Boundary conditions are applied on the surface of domain to define the foam and solid phases. Inlet and outlet region are define to study foam-solid flow. Input and output condition for validation case is applied at annulus as shown in Figure 3.3

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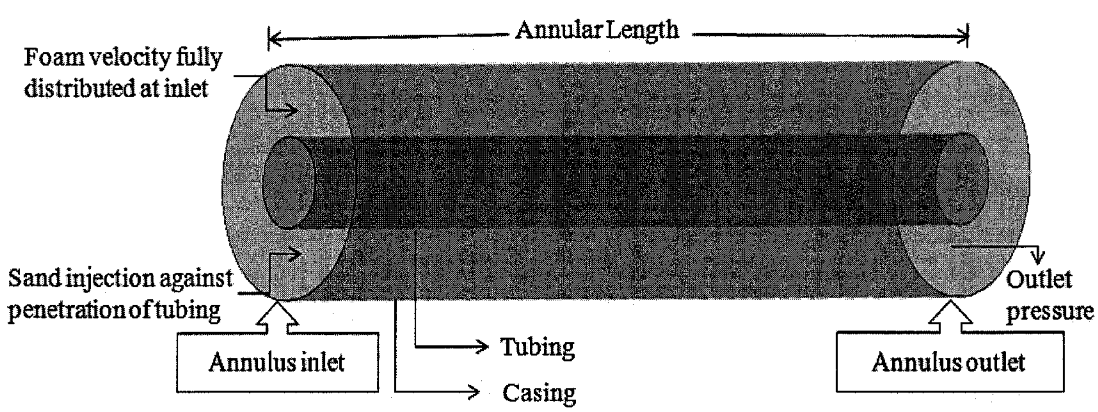


Figure 3.3: Schematic well diagram

3.5.1 Inlet condition

Inlet is the region where flow starts and directs into the domain. The bottom of wellbore is taken as inlet region. There are many ways to apply the inlet boundaries and these initial conditions depend upon the particular model used for numerical analysis. To define the inlet boundaries, there are many type of combination for mass and momentum transfer equations. Values are specified directly at inlet. The foam velocities, varied from 3 to 6-ft/sec, are applied at annulus inlet. The rate of penetration of tubing inside the fill is taken as 60-ft/hr. Particle shape is spherical having an average diameter of 3 mm. There is a uniform injection of fill particles at annulus inlet. Injection flow rate of solid particles are calculated using following equation.

$$Q = \rho VA \tag{3.24}$$

where, Q is the mass flow rate, ρ is the density of fill, V is the velocity of particle and A is the area of annulus.

3.5.2 Outlet condition

Outlet is the region where outflow was expected. Atmospheric pressure has been applied at annulus outlet. The outlet relative pressure allowed the pressure profile at the annulus outlet to vary based on the upstream influences while average pressure specified at the outlet initially, where:

$$\overline{P}_{Spec} = \frac{1}{A}\int_S p_{ip} dA \tag{3.25}$$

where, p_{ip} is the imposed pressure at each integration step and the integral was solved over the whole boundary surface.

3.5.3 Walls condition

As walls are the solid boundaries so these allow the transfer of heat into and out of domain through fixing flux value condition at wall inside and outside. But there is no variation of temperature in the horizontal zone so there is no specification of heat flux. Also, wall surface is taken as smooth i.e. there is no roughness outside the tubing and inside the casing. In the present study, velocity of the foam at the wall boundary and wall shear stress are set to zero, hence the boundary condition at the wall becomes:

$$U_{wall} = 0 \tag{3.26}$$

$$\tau_{wall} = 0 \tag{3.27}$$

3.6 Mesh formation

Annular geometry is meshed using ANSYS workbench CFX as shown in Figure 3.4. The geometry is meshed into hexahedral cells resulting into 502600 elements and 603920 nodes.

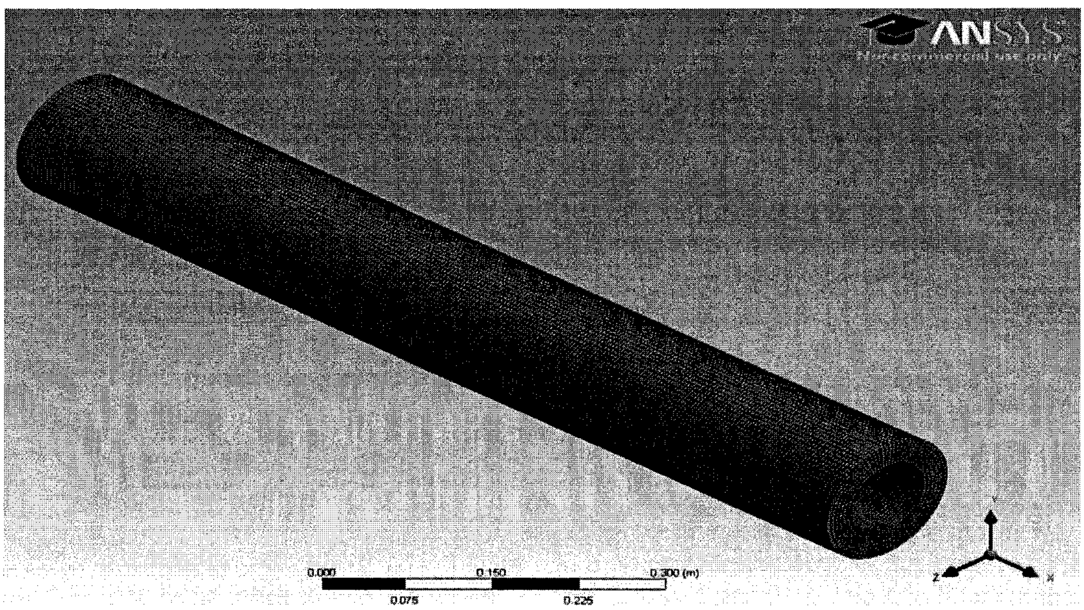


Figure 3.4: Refine mesh of annular section

3.6.1 Mesh adoption

There are many methods to perform mesh adoption. Mesh adoption mean that the mesh is refined in the required area and this refinement depends upon the adoption criteria. As the adoption criteria method is "solution variation", so the adoption criteria, for given mesh edge and length is calculated as:

$$A_i \sum_j \frac{|\Delta\varphi_{ji}|}{N_{\varphi j}|\Delta\varphi_j|} \tag{3.28}$$

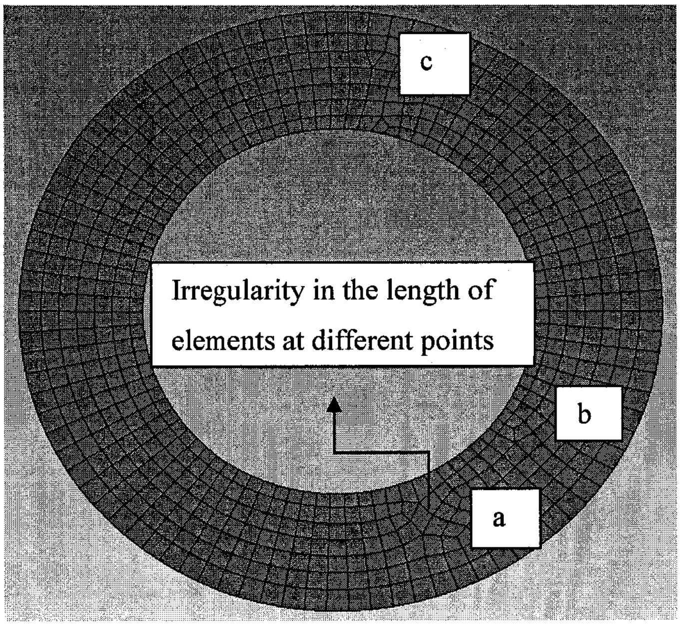
where, φ_j is the jth adoption variable such as density, pressure and so on, $\Delta\varphi_j$ is the global range of variable φ_j over all the nodes, $\Delta\varphi_{ji}$ is the difference between φ_j at one and other end of edge, and N_{φ_j} is a scale for adoption variable j to scale all the A_i to take value between 0 and 1.

3.6.2 Mesh refinement implementation

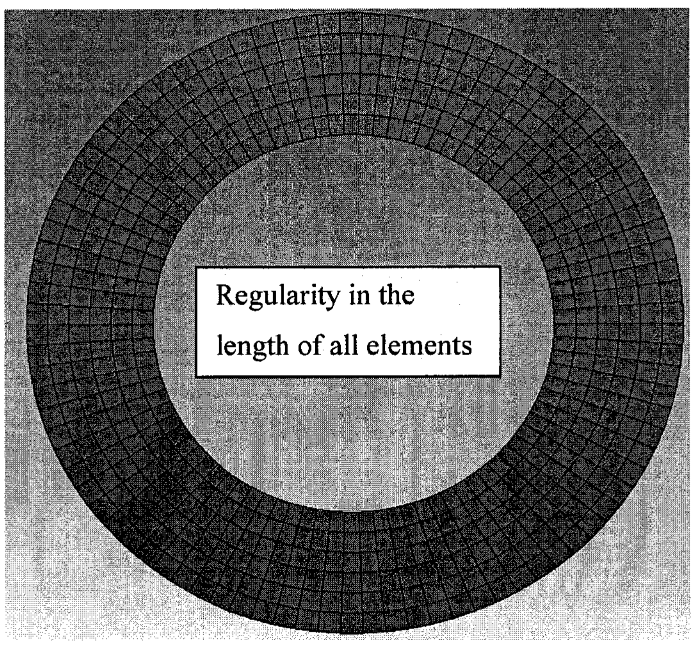
In this study hierarchical refinement is used to meet the adoption criteria. In this method there is structured refinement of already created mesh. There is a sequence of refinement to reach a set of hierarchical level. In each mesh adaption, each meshed edge has an extra node placed half way along it. The mesh elements that share the edge are divided to use more nodes, as follows:

- Neighboring elements differ by one refinement level
- All the edges of elements are divided into two and elements split up accordingly.
- As extra nodes are added to an edges so all mesh element which share that edges are refined.
- In the refined mesh only hexahedron elements are chosen.

Formation of mesh without refinement is shown in Figure 3.5 (a) . At the inlet and outlet faces, refinement was carried out to meet the mesh adoption criteria which are shown in Figure 3.5 (b).



(a)



(b)

Figure 3.5: Mesh without and with refinement of annular face: (a) Mesh without refinement, (b) Mesh with refinement

3.7 Mesh dependency check analysis

This analysis is carried out to study the mesh dependence convergence behavior. Numerical analyses have been studied at various mesh densities. It is illustrated in Figure 3.6 that responses of pressure value remain unchanged when the mesh density per unit volume is 4. The size of each element at this density is 0.5 meter. Mesh dependent study shows that response is more accurate at fine mesh size.

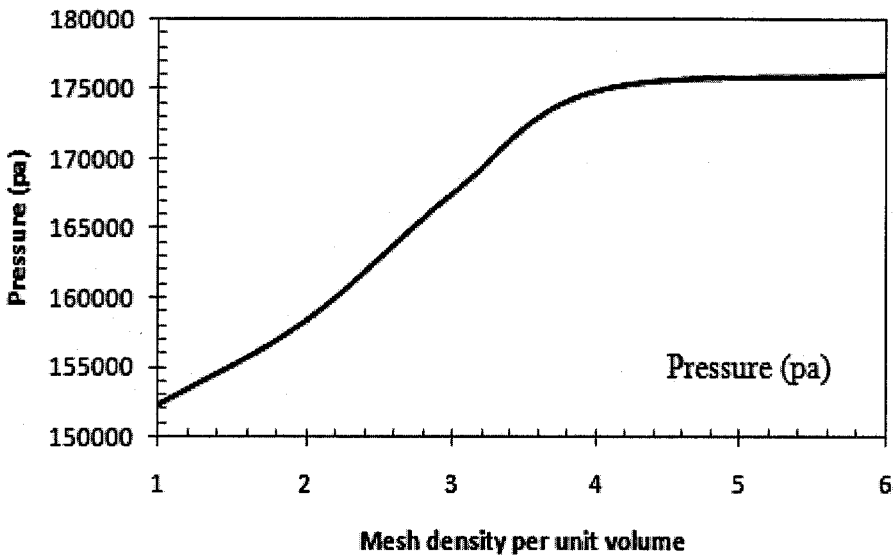
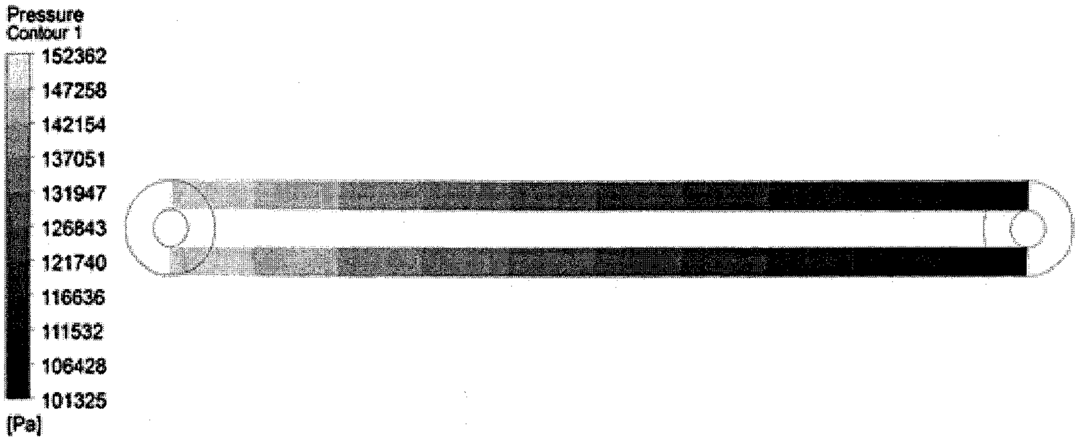
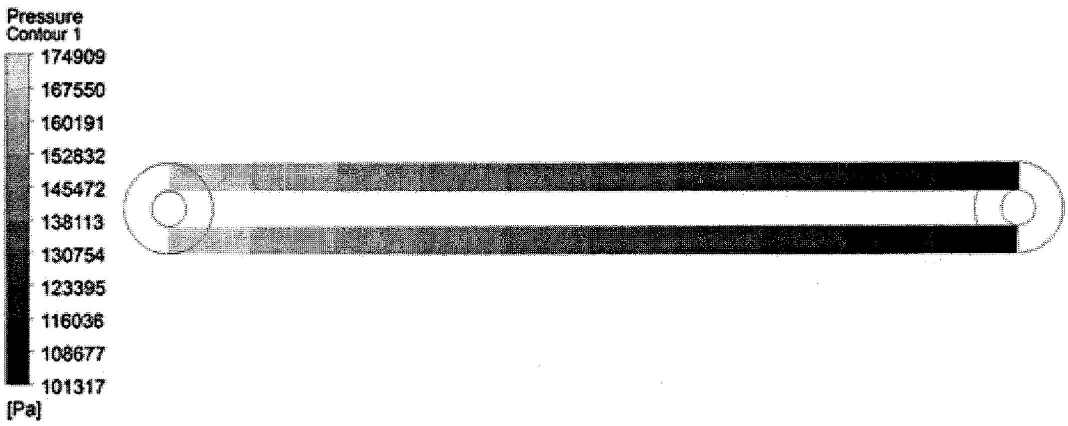


Figure 3.6: Pressure convergence versus element division

Figure 3.7 illustrate the comparison of pressure at higher and lower mesh densities. Different contours are shown in Figure 3.7 (a), (b) and (c) which have maximum face sizes of 0.8, 0.5 and 0.4 m respectively. It can be noticed that counter difference decreases when mesh density per unit volume is increased to 6. The present study is carried out with maximum face size of 0.4 m which consists of 502600 elements.



(a)



(b)

(c)

Figure 3.7: Comparison of pressure contours along wellbore at various mesh densities: (a) Pressure contour when mesh density per unit volume is 1, (b) Pressure contour when mesh density per unit volume is 4, (c) Pressure contour when mesh density per unit volume is 6

3.8 Material properties

In order to setup the numerical study, it needs to be defined in CFX Pre by defining the following:

- Properties of foam
- Properties of fill

Foam is considered as homogenous and non-Newtonian fluid whose rheological property can be presented by a Herschel-Buckley viscosity model as follow:

$$\tau = \tau_o + k(\gamma)^n \tag{3.29}$$

where, τ is the shear stress, γ is the shear rate, τ_o is the yield stress, n is the exponent and k is the consistency index

Herschel-Bulkley viscosity model parameters for water base foam was analyzed by Miska et al.[57] as shown in Table 3.2.

Table 3.2: Properties of foam

Liquid Phase	Parameters	Quality (%)		
		70	**80**	**90**
Water (Base Fluid)	$\tau_0(Pa)$	0.0004	0.000009	0.001379
	$K(Pa.s)$	0.6894	1.999	2.8268
	n	0.53	0.45	0.42

Fill properties are introduced in the material list as shown in Table 3.3.

Table 3.3: Properties of Fill [3]

Fill Property	Value
Material	Gravel
Density (kg/m^3)	2600

After introducing the material, setup is run for simulation. CFX solves the governing equations iteratively by integrating partial differential equation over the volume across the region of interest. These equations are converted to a system of algebraic equations which are then solved iteratively.

3.9 Track of solid particles

In this setup fill particles are modeled according to particle transport theory. The CFX Lagrangian particle transport multiphase module that can model the distribution of solid particles in a continuous fluid phase was used for the analysis. The Lagrangian model tracked individual solid particles through the continuous fluid starting at the area of injection until the particles were out of the area of interest. The particle tracking was performed by creating a set of regular equations in time for individual particles. These equations were then integrated by making use of a simple integration scheme for calculating the behavior of the particles as they moved through the flow area.

3.9.1 Particle displacement

The displacement of the particle is calculated using forward Euler integration of each particle velocity over time step as given below

$$x_i^n = x_i^o + v_{pi}^o \delta t \tag{3.30}$$

where, x is the particle displacement, n is the new position of sand particle, o is the old position of particle, v_p is the particle velocity and δt is the time step.

3.9.1 Particle velocity

The particle velocity v_p is defined as:

$$v_p = x_f + (v_p^o - v_f)\exp(-\frac{\delta t}{\tau}) + \tau F_{all}(1 - \exp(\frac{\delta t}{\tau})) \tag{3.31}$$

where, v_f is the foam velocity, τ is the shear stress and F_{all} is the sum of all forces.

3.10 Concluding remarks

Figure 3.8 summarizes the entire work flow for setting up the model within the ANSYS CFX-14 for numerical study of fill transport using foam.

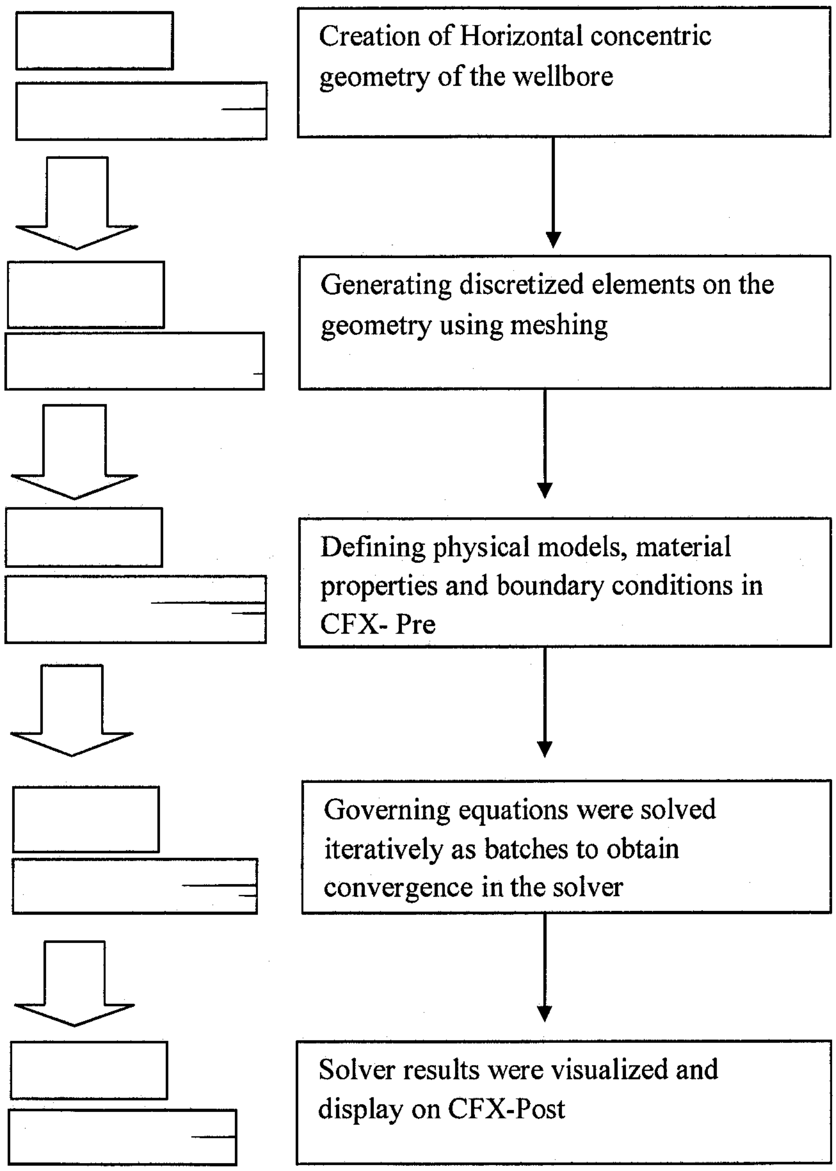


Figure 3.8: Work flow summary of numerical study

This chapter discussed a methodology of present study, together with the set of general expressions to calculate the fill concentration and pressure drop. A concentric annulus geometry was created for fill concentration analysis. Annular section of wellbore was discretized into 502600 elements and 603920 nodes. The associated mathematical model for foam and solid particles were applied to introduce the two phase flow. Foam and Fill properties were introduced to apply the physical models and boundary conditions. After applying physical modes, governing equations were solved iteratively as batches to obtain the convergence in the solver. Eulerian-Eulerian model is adopted for foam-solid mixture and Lagrangian particle transport model is used to track the solid particles. The Lagrangian model tracked solid particles through the continuous fluid starting at the area of injection until the particles were out of the area of interest. The particle tracking was performed by creating a set of regular equations in time for individual particles. These equations were then integrated by making use of a simple integration scheme for calculating the behavior of the particles as they moved through the flow area. Advance scheme used high resolution and 0.0001 convergence criteria to solve the equations. Solver results were visualized and displayed on post processor. In the next chapter, the validation of model and parametric study will be discussed.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the detail results of the simulation model. Initially, model is validated with the experimental and numerical results which include the rotation of inner pipe. Study is forwarded without the rotation of inner pipe. This study includes fill transport through concentric annulus. Fill settlement is also studied at different qualities and velocities of foam. The results of foam-solid flow behavior in the different CT/Annulus diameters were simulated to predict the fill concentration along the horizontal wellbore.

4.2 Model Validation

In the present study, numerical model has been validated with the experimental study which was carried out by Chen et al. [48]. It was noticed that the particles concentration was matched favorably with the experimental study. Numerical model was also verified with the foam flow hydraulics model developed by Chen et al. [58]. There is agreement in the pressure drop calculated with present numerical model and their mathematical model. Input parameters used for the numerical model validation are shown in Table 4.1.

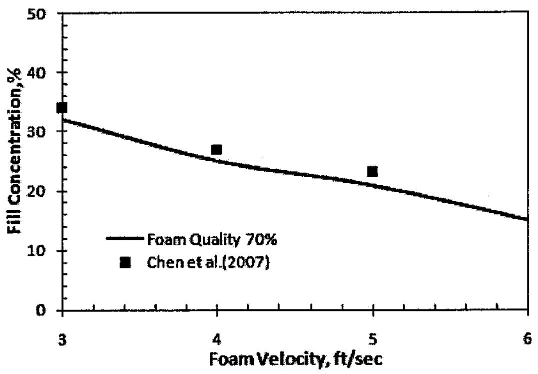
Table 4.1: Input parameters for validation

Foam quality (%)	**Foam velocity (ft/sec)**	**Fill diameter (mm)**	**Pipe diameter (inch)**	**Casing diameter (inch)**	**Pipe rotation (RPM)**
70	3, 4, 5, 6	3	7.8	3	120
80	3, 4, 5, 6	3	7.8	3	120
90	3, 4, 5, 6	3	7.8	3	120

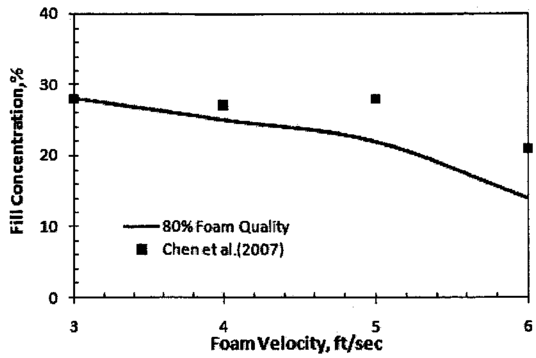
4.2.1 Verification with experiments

Chen et al. [48] performed experiments to study drilling cutting concentration in the horizontal annulus versus foam velocities with three foam qualities of 70, 80 and 90%. Their test section consisted of annulus with 5.76" outer casing and a 3.5" drillpipe inside. Centralizers are placed around the inner pipe to keep the drill pipe at the centre of the annulus. Present study shows the comparison of simulated and experimental study on solid particles concentration in the annulus against different velocities of foam. Numerical results are closest to the experimental data especially when the foam quality is higher.

Figure 4.1 (a) illustrate the effects of different velocities of 70% quality foam on particle removal along horizontal wellbore. It can be seen that there is almost same concentration of solid particles in both studies. Shown in Figure 4.1 (b) is the fill removal rate with 80% quality foam. In the present study, removal of solid particle is according to experimental data at lower velocities e.g. 3 and 4-ft/sec. It can be seen from present study that as velocity is increasing, fill concentration is decreasing because concentration of particles is inversely proportional to the velocity of the cleaning fluid. However, the experimental data from Chen et al. [48] showed that fill concentration is increasing for foam velocity higher than 5-ft/sec. This non-monotonic increase in the particles concentration may due to artifacts in data acquisition device because solid concentration must decrease with increase in velocity. Figure 4.1 (c) shows the effect of different velocities on the fill concentration for the 90% quality foam. In the present study, fill removal rate is following the trend of the experimental data.



(a)



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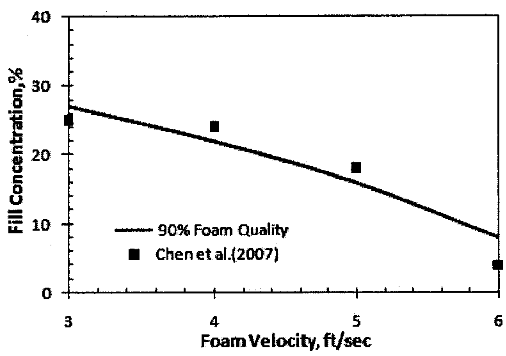


(c)

Figure 4.1: Verification of numerical solution with experimental data: (a) Fill concentration at 70% quality foam, (b) Fill concentration at 80% quality foam, (c) Fill concentration at 90% quality foam

4.2.2 Verification with mathematical model

Figure 4.2 presents the profile of the pressure gradient for the foam quality at 70, 80 and 90% at the same inlet velocity. Foam quality of 70% had a minimum drop in pressure of 0.03 psi/ft which was almost the same as the drop in pressure that Chen et al. (2009) had calculated. The increase in the pressure gradient was related to the quality of the foam. The quality of the foam at 90% showed the highest pressure gradient. This is as a result of increase in the shear stress at the wall. With the increase in the wall shear stress the removal of the fill became easier, which resulted in more cleaning efficiency.

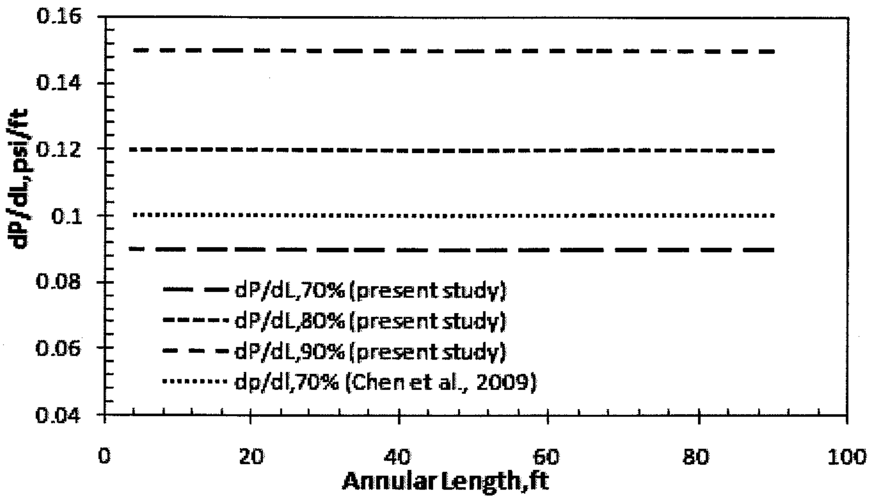


Figure 4.2: Annular pressure gradient vs. horizontal annular length

4.3 Fill settlement identification during coiled tubing cleanup operation

Fill concentration was plotted along the longitudinal direction of the horizontal well for foam velocities ranging from 3-6ft/sec for the 70%, 80% and 90% foam qualities. It was found that removal of fill concentration is inversely proportional to the fluid velocity.

4.3.1 Fill settlement with 70% quality foam

As shown in Figure 4.3, the concentration of the fill was noticed along each point of the horizontal well at foam velocities ranging from 3 to 6-ft/sec for the 70% quality foam. The contour is showing the settlement of fill along the lower side of the annulus. There is higher settlement of fill particles at low velocity of foam e.g. 3-ft/sec, therefore fill bed formation occur at low velocity. As the weight of the fill is higher than the buoyancy force, particles settle down and form a continuous solid bed. It was also noticed that as the distance grew, the removal of the fill at low velocities became difficult. Fill bed was thus formed as the particles started settling down along the wellbore. The average fill concentration was reduced to 32% with the increase in velocity for only 1-ft/sec. Furthermore, an 18% fill concentration was seen with a further increase in the foam velocity along the annulus. It was also observed that at 6-ft/sec a greater suspension of the fill particles was obtained. At a higher velocity, e.g., 6-ft/sec, there was a concentration of the fill at 9% along the annulus. It can be observed that there is reduction of fill bed formation at higher velocity because buoyancy force overcomes the gravity force. Fill suspension pattern can be observed at higher velocity e.g. 6-ft/sec.

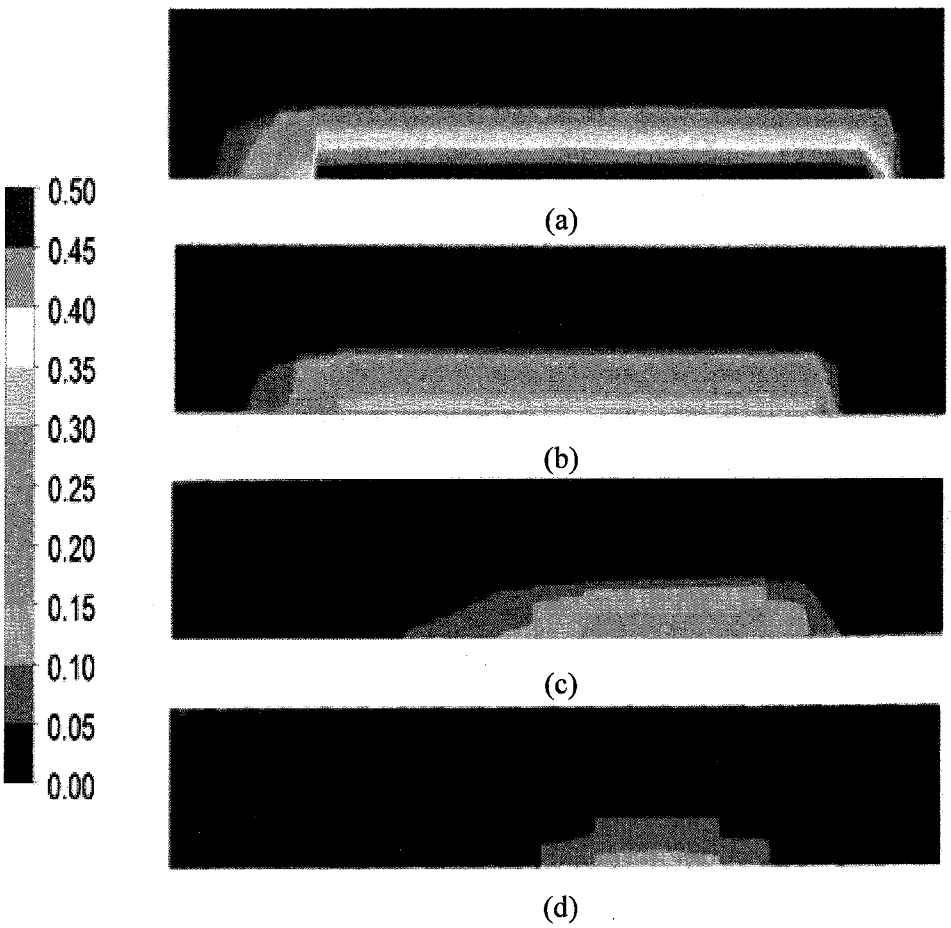


Figure 4.3: Fill bed formation along the bottom of the annulus for 70% quality foam: (a) Fill settlement at foam velocity of 3-ft/sec, (b) Fill settlement at foam velocity of 4-ft/sec, (c) Fill settlement at foam velocity of 5-ft/sec, (d) Fill settlement at foam velocity of 6-ft/sec

4.3.2 Fill settlement with 80% quality foam

Figure 4.4, shows that the concentration of the fill was 10% near the start of cleaning section of the wellbore, at a low velocity, e.g., 3-ft/sec which was acceptable. The settlement of fill particle increased with the passage of flow and the concentration of the fill became 30% which indicated the formation of a fill bed at the lower side. It was noticed that further increase in velocity resulted in 20% concentration of particles along the annulus. Moreover, for velocities that is higher, such as between 5 and 6-ft/sec, it has been observed that very good cleaning has taken place due to suspension of particles. As the suspension of fill increased, then concentration of particles reduced to around 10% for 80% quality foam.

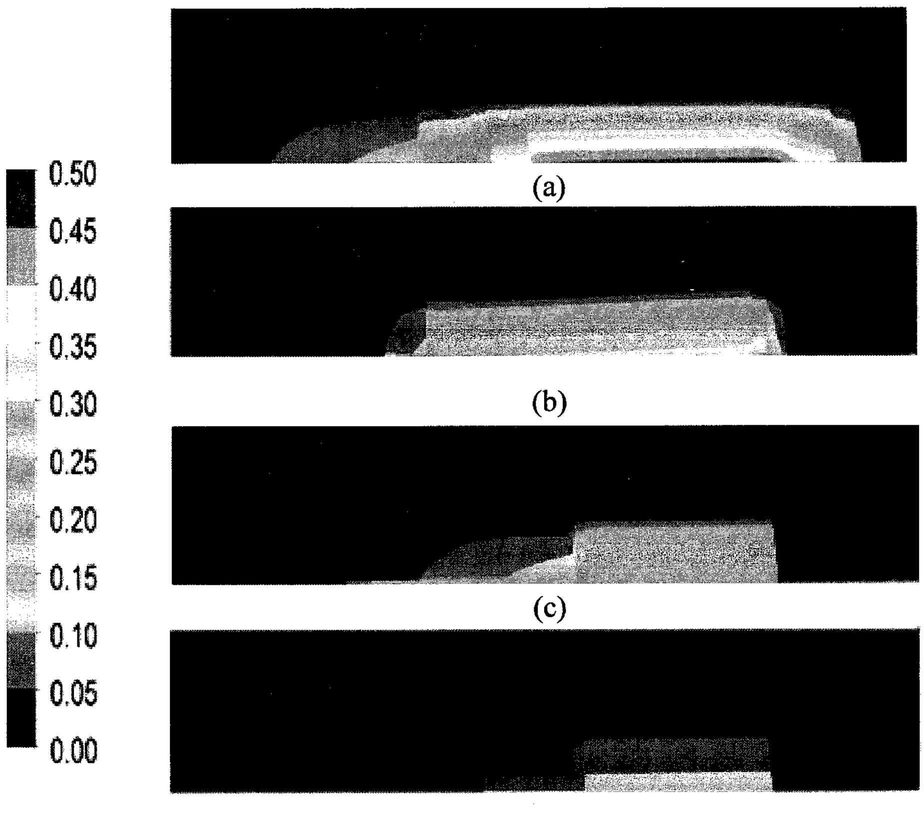


Figure 4.4: Fill bed formation along the bottom of the annulus for 80% quality foam: (a) Fill settlement at foam velocity of 3ft/sec, (b) Fill settlement at foam velocity of 4ft/sec, (c) Fill settlement at foam velocity of 5ft/sec, (d) Fill settlement at foam velocity of 6ft/sec

4.3.3 Fill settlement with 90% quality foam

The settlement of fill along the annulus for the 90% quality foam is shown in Figure 4.5. It can be seen that 90% quality foam had a greater suspension even at low foam velocities hence there is less concentration of particles. As the distance increased, removing the fill becomes harder. Particles settled along the longitudinal direction of the well when the velocity is low. The most efficient clean-up was noted at velocity around 6-ft/sec. The 90% quality form possesses a high suspension power, and thus the buoyancy force overcomes the gravitational pull along the longitudinal direction of the well. It can be noticed, that the amount of fill concentration is less than 8% along the annulus for high quality foam because of highest suspension of the particles.

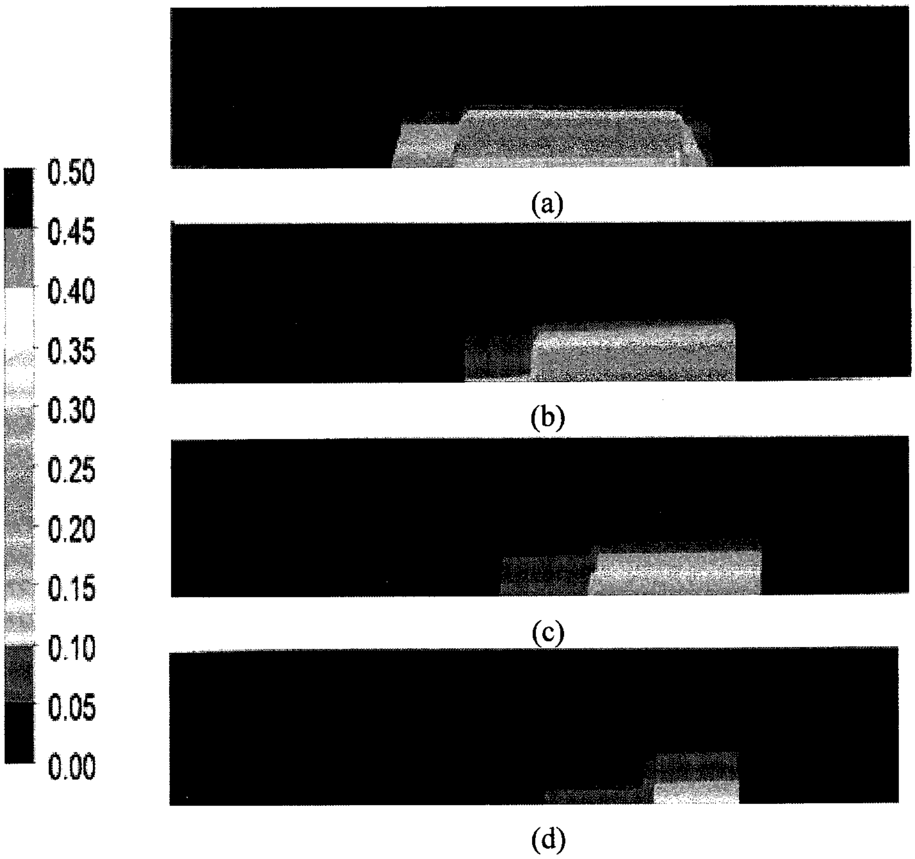


Figure 4.5: Fill bed formation along the bottom of the annulus for 90% quality foam: (a) Fill settlement at foam velocity of 3ft/sec, (b) Fill settlement at foam velocity of 4ft/sec, (c) Fill settlement at foam velocity of 5ft/sec, (d) Fill settlement at foam velocity of 6ft/sec

4.4 Fill concentration along the wellbore for 70, 80 and 90 % qualities foam

After validation of numerical model, concentration of fill particles was calculated along the annulus when there is no rotation of tubing. In this case particles were tracked along the annulus length. Fill concentration was calculated along annular length of wellbore. It was recorded that higher fill concentration occurred at lower foam velocity e.g. 3-ft/sec.

4.4.1 Fill concentration at 70% quality foam

As shown in Figure 4.6, the concentration of the fill was noticed along each point of the horizontal well at foam velocities ranging from 3-6ft/sec for the 70% quality foam. It was also noticed that as the wellbore distance increased, the removal of the fill at low velocities became difficult, and a fill bed was formed as the particles started settling down along the wellbore. The observation was made that the fill concentration was reduced to 32% with the increase in velocity for only 1-ft/sec. Furthermore, an 18% fill concentration was seen with a further increase in the foam velocity along the annulus. It was also observed that at 6-ft/sec a greater suspension of the fill particles was obtained. At a higher velocity, e.g., 6-ft/sec, there was a concentration of the fill at 9% along the annulus. During the continuous fluid circulation along the well, it was acceptable to have a less than 10% particle concentration.

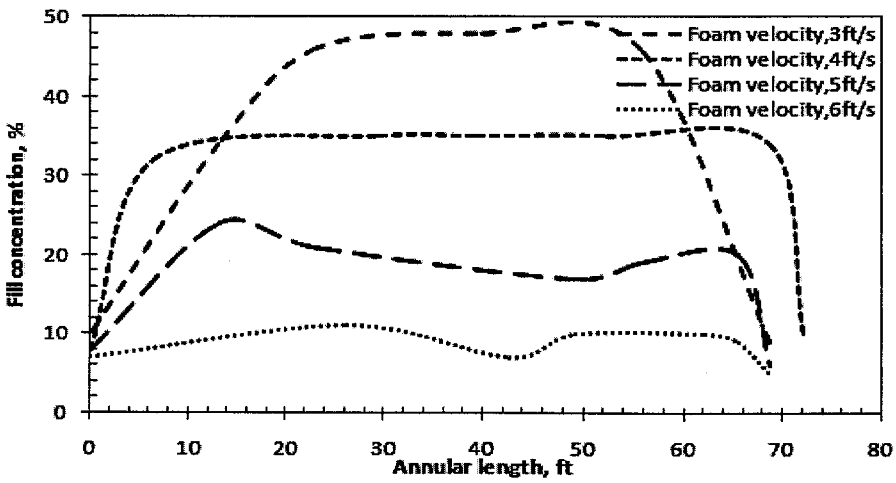


Figure 4.6: Fill concentration along the horizontal annulus at 70% quality foam

4.4.2 Fill concentration at 80% quality foam

Figure 4.7 shows that the concentration of the fill was 10% at the start, at a low velocity, e.g., 3-ft/sec which was acceptable. The concentration of the fill became 30% as the wellbore distance increased which indicated the formation of a fill bed at the bottom side. Investigation has shown that efficient removal is possible with only a 1-ft/sec increase in the velocity. Moreover, for velocities that is higher, such as between 5 and 6-ft/sec, it has been observed that very good cleaning has taken place. It was investigated that there is a good fill removal at 5-ft/sec for 80% foam quality as compared to 70% quality foam. The concentration of particles is approximately 20% for 70% quality foam and decreased to 10% at same velocity for 80% quality foam.

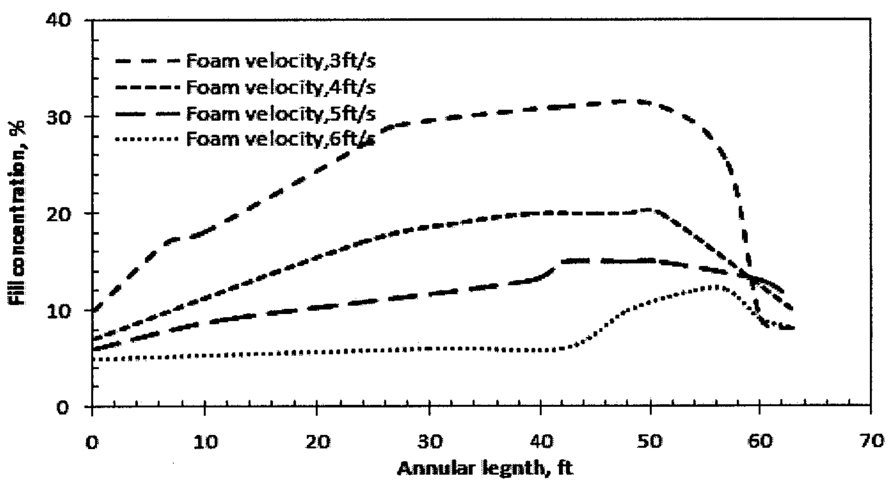


Figure 4.7: Fill concentration along the horizontal annulus at 80% quality foam

4.4.3 Fill concentration at 90% quality foam

The concentration of fill along the annulus for the 90% quality foam is shown in Figure 4.8. It can be seen that the 90% quality foam had a greater suspension even at low velocities. As the wellbore distance increased, removing the fill becomes harder; moreover, particles dropped down the wellbore along the lower side for velocities of lower values, e.g., 1 and 2-ft/sec. The most efficient clean-up was noted at the velocity around 6-ft/sec. It can be noticed that as velocity increase to 5-ft/sec, fill concentration decreases to almost 15% along the annulus. The highest cleaning efficiency is observed at a velocity of 6-ft/sec, where the amount of fill concentration is less than 8% along the annulus for 90% quality foam.

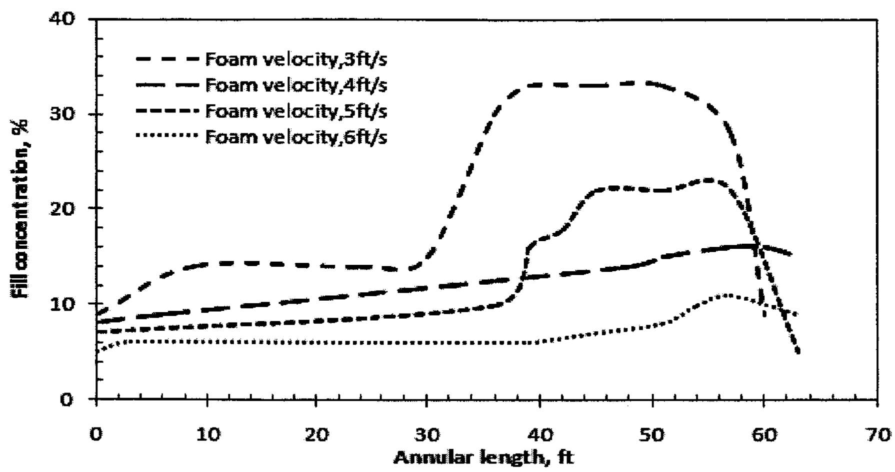


Figure 4.8: Fill concentration along the horizontal annulus at 90% quality foam

4.5 Fill concentration and pressure drop at different diameter ratios

The effects of foam quality, velocity and varying particle size on fill concentration and pressure drop at different CT/Annulus diameter ratios in concentric horizontal wellbore are discussed in the subsections below.

The parameters used for numerical analysis of fill concentration and pressure drop during coiled tubing cleanup operation are shown in Table 4.2. In addition, inner tubing is concentric and there is no rotation.

Table 4.2: Data for parametric study

Foam quality (%)	**Foam velocity (ft/sec)**	**Fill diameter (mm)**	**Diameter ratio (CT/Annulus)**
70	3, 4, 5, 6	0.5, 1, 2, 3	0.35, 0.40, 0.45, 0.50
80	3, 4, 5, 6	0.5, 1, 2, 3	0.35, 0.40, 0.45, 0.50
90	3, 4, 5, 6	0.5, 1, 2, 3	0.35, 0.40, 0.45, 0.50

4.5.1 Effect of foam qualities on fill concentration

The relationship between the concentration of the fill and the quality of the foam at each diameter ratio and constant foam velocity of 6-ft/sec is presented in this section. It is found that for all particle sizes, higher foam quality removes fill more efficiently than lower foam quality. There is a decreasing trend in fill concentration as foam quality increases for all of the diameter ratios and fill sizes. Effect of foam quality on fill concentration is discussed in two different ways as given below;

4.5.1.1 Percentage reduction in fill concentration

Figure 4.9 (a) shows the percentage decrease of fill concentration for 0.5 mm particle size when foam quality varies from 70 to 90% and flowing at 6-ft/sec in varying diameter ratios from 0.35 to 0.50. There is a significant decrease in fill concentration when the quality of foam is less than 80%, however, this decrease becomes almost insignificant above 80% foam quality. For example, at a constant diameter ratio of 0.50, there is 30% decrease in fill concentration as foam quality increases from 70 to 80%. However, 20% decrease is recorded as foam quality increases from 80 to 90%.

Furthermore, similar observations could be witnessed in Figures 4.9 (b), 4.9 (c) and 4.9 (d) with particle sizes of 1 mm, 2 mm and 3 mm respectively. It could be noticed that at a diameter ratio of 0.50, for example, fill concentration decreases by 35%, 30% and 25% as foam quality increases from 70 to 80% in Figures 4.9 (b), 4.9 (c) and 4.9 (d) respectively. At increasing foam quality from 80 to 90%, however, fill concentration reduced to 18%, 16% and 12% in Figures 4.9 (b), 4.9 (c) and 4.9 (d) respectively. Generally, the density of the foam reduces drastically as foam quality increases. This density change has greater effect on cuttings slip velocity than it does on viscosity. As a result, the cuttings slip velocity increases as foam quality increases. An increase in cuttings slip velocity will thus retard the removal of fill concentration as foam quality increases; an incident which could be observed as foam quality increases from 80 to 90% in Figures 4.9 (a) to 4.9 (d)

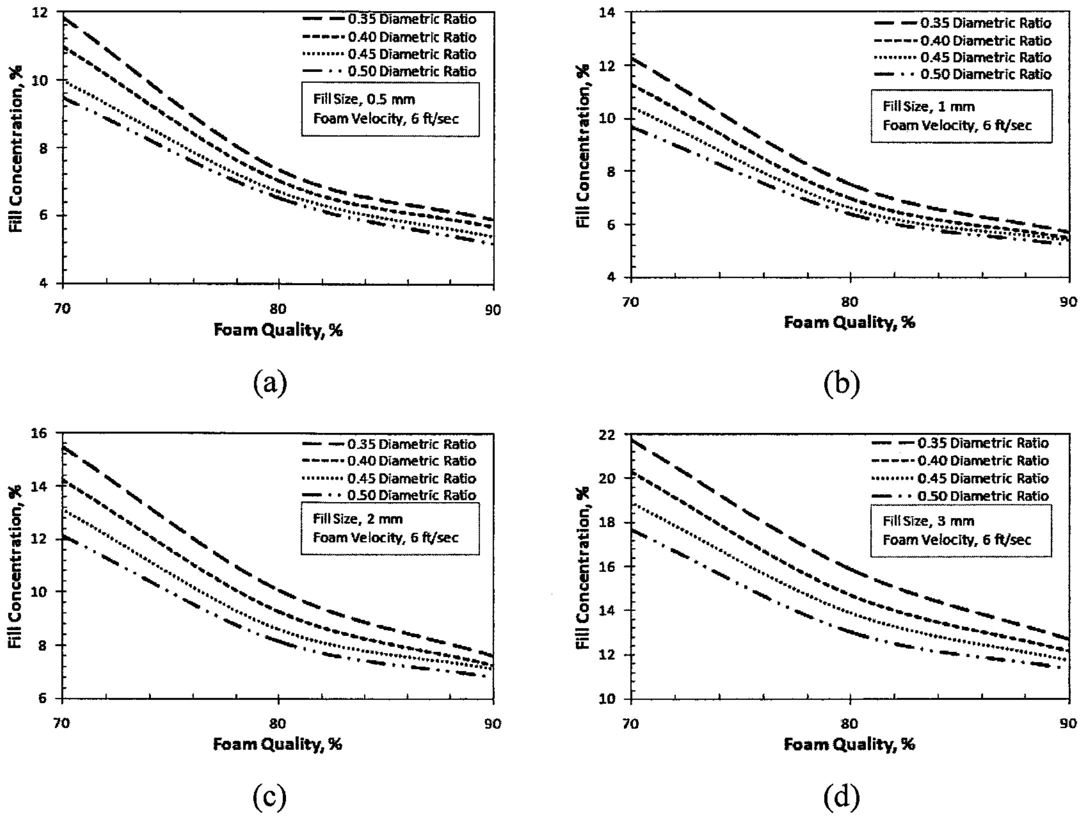


Figure 4.9: Effect of foam qualities on fill concentration: (a) fill size of 0.5mm (b) fill size of 1mm (c) fill size of 2mm (d) fill size of 3mm

4.5.1.2 Slope reduction in fill concentration

In the above Figure 4.9 (a) there is a decrease of fill gradient for 0.5 mm particle size when foam quality varies from 70 to 90%. It shows a significant decrease in fill concentration when quality of foam is less than 80%. It can be noticed that fill gradient at low quality foam is 0.37 and it reduces to 0.13 when foam quality increases from 80 to 90%. Fill gradient at low quality is around three time the gradient at high quality. It is also found that diameter ratio has high effect on particle removal when foam quality is 70%. Surprisingly, it is found that the effect of diameter ratio reduces when foam quality is 80% or above. At 1 mm particle size , percentage decrease in fill concentration is also high at low quality foam and it decreases when foam quality is 80% or above as shown in Figure 4.9 (b). Fill gradient at low quality foam is 0.40 and it reduces to 0.14 as foam quality increases from 80 to 90%. It can be noticed that the decrease in fill gradient at low foam quality is also three time the decrease at high foam quality for particle size of 1 mm.

Figure 4.9 (c) shows the percentage decrease in fill concentration at increasing foam quality from 70 to 90% at constant velocity of 6-ft/sec. Fill gradient becomes two times the gradient at low quality when particle size is 2 mm. Average fill gradient is 0.47 at low foam quality and it increases to 0.18 when foam quality increases from 80 to 90%. Also, diameter ratio has high impact on fill concentration at foam quality less than 80%. Similarly, Figure 4.9 (d) shows the percentage decrease of fill for 3 mm particle size when foam quality varies from 70 to 90%. The average fill gradient is 0.51 at low foam quality and it reduces to 0.24 when foam quality increases from 80 to 90%. Chen et al. [17] also found in their study that low foam quality is more efficient to remove solid particles as compared to high foam quality. Furthermore, the slope of fill concentration was analyzed as indicated in **Error! Reference source not found.**

Table 4.3: Gradient ($\partial C / \partial Q$) of fill concentration at different foam qualities

Particle size (mm)	**Gradient at low foam qualities (70-80%)**	**Gradient at high foam qualities (80-90%)**
0.5	0.37	0.13
1	0.40	0.14
2	0.47	0.18
3	0.51	0.24

Figure 4.10 shows that reduction of fill concentration is very high at low foam quality. There is insignificant change in the fill gradient for the small particle size particles which ranges from 0.5 to 1 mm. As the particle size increases from 1 mm then there is a prominent change in the gradient. It can be noticed that as the particle size increase to 3 mm than fill gradient at low foam quality becomes two times as compared to high foam quality.

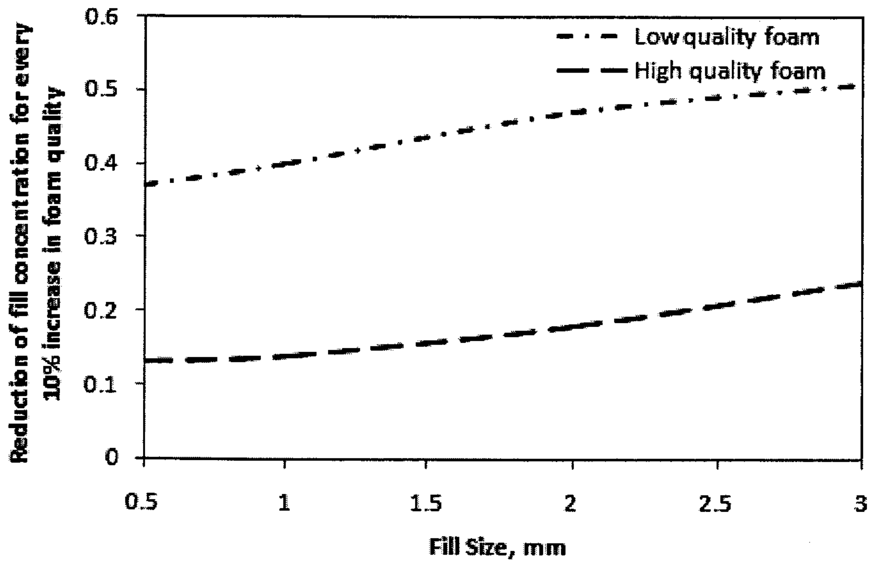


Figure 4.10: Fill gradient at high and low foam qualities

4.5.2 Effect of foam velocities on fill concentration

In all of the studies, a decreasing trend for the fill concentration is noticed as fluid velocity increases for all of the CT/Annulus diameter ratios and fill sizes. The relationship between the concentration of the fill having size of 0.5 to 3 mm and the velocity of the foam at each diameter ratio is presented in this section. Effect of foam velocity on fill concentration is discussed in two different ways as given below;

4.5.2.1 Percentage reduction in fill concentration

In Figures 4.11 (a) to 4.11 (d), the effect of foam velocity is clearly seen to play a significant role in reducing the fill concentration within the wellbore. In each case, the influence of a fluid of 90% foam quality flowing at varying velocities from 3-ft/sec to 6-ft/sec on fill concentration and having constant particle sizes of 0.5 to 3mm, in different annular sizes of diameter ratios of 0.35 to 0.50 is observed. For smaller particle sizes, for example 0.5 mm and 1 mm, a large percentage of fill concentration is removed especially at low foam velocities of 3-ft/sec to4-ft/sec, however, no significant percentage decrease of fill concentration results at high foam velocity of 5-ft/sec to 6-ft/sec for all diameter ratios (see Figures 4.11 (a) and 4.11 (b)). For larger particle sizes, such as 2 mm and 3 mm, there is almost a constant rate of percentage decrease in fill concentration as foam velocity increases from 3-ft/sec to 6-ft/sec for all diameter ratios as shown in Figures 4.11 (c) and 4.11 (d).

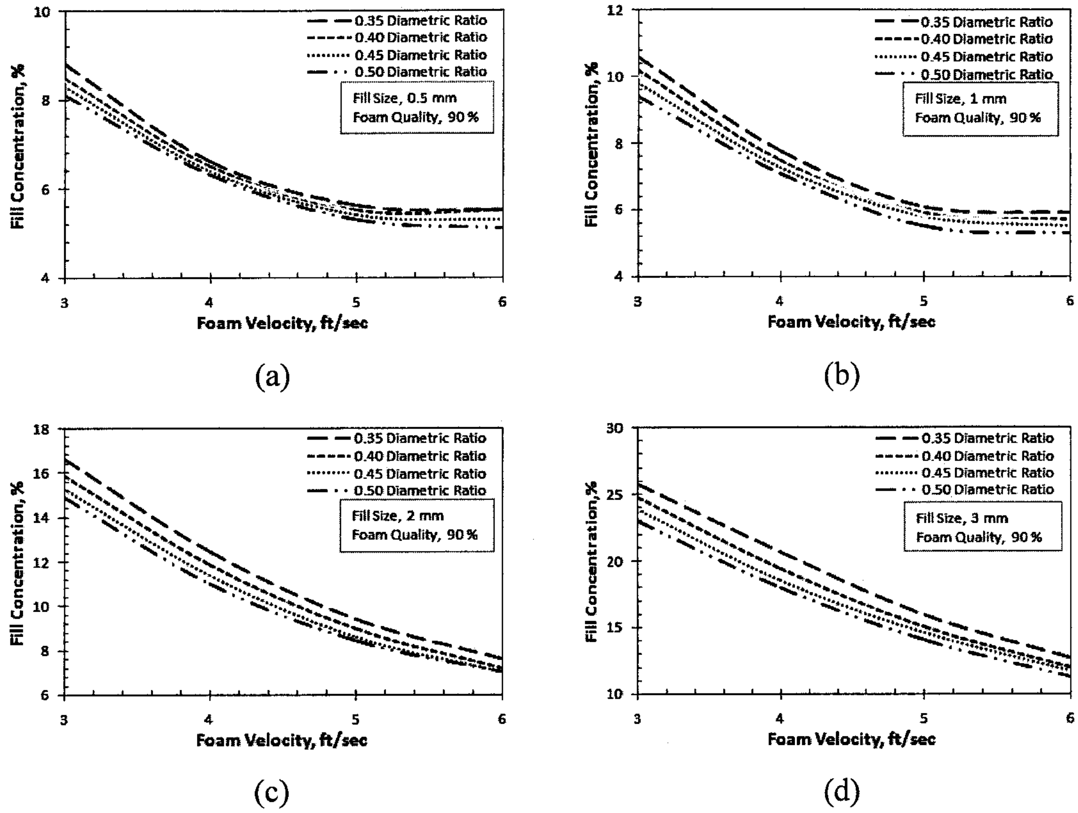


Figure 4.11: Effect of foam velocities on fill concentration: (a) At fill size of 0.5 mm, (b) At fill size of 1 mm, (c) At fill size of 2 mm, (d) At fill size of 3 mm

4.5.2.2 Slope Reduction in fill concentration

Above mentioned Figure 4.11 (a) also presents fill gradient of 0.5 mm size in the annulus for varying foam velocities and CT/Annulus diameter ratios at 90% quality foam. It can be noticed from the graph that as the foam velocity increases from 3 to 5-ft/sec, there is a higher decrease in the fill concentration. As the velocity increases from 5 to 6-ft/sec, there is no significant change in the fill concentration. There is high fill gradient around 1.5 at low foam velocity, i.e. at 3 to 5-ft/sec. As, the foam velocity increases from 5-6 ft/sec, fill gradient decrease to 0.1. Fill concentration of 1mm size in the annulus for varying foam velocities at 90% quality foam and CT/Annulus diameter ratios is shown in Figure 4.11 (b). It can be seen from the graph that there is a significant decrease in the fill concentration when the foam velocity increases from 3 to 5-ft/sec. As the velocity increases from 5 to 6-ft/sec, there is also no considerable change in the fill concentration. Fill gradient around 2 is calculated at low foam velocity and it decreases to 0.2 at high foam velocity when fill size is 1 mm.

Figure 4.11 (c) shows the percentage decrease in fill concentration of 2 mm particle size at increasing foam velocity from 3 to 6-ft/sec with 90% quality foam. For fill size of 2 mm, when foam velocity is increased from 3 to 5-ft/sec, fill concentration significantly decreases to 9% ; however, when foam velocity is increased further from 5 to 6-ft/sec, fill concentration in the annulus reduces to 7%. There is a higher fill gradient around 3 at low foam velocity and it decreases to 1.6 at high foam velocity when fill size is 2 mm. Similarly, Figure 4.11 (d) shows fill concentration of 3 mm particle size in the annulus for varying foam velocities at 90% quality foam and CT/Annulus diameter ratios. Fill gradient around 4.7 is observed at low foam velocity and it decreases to 2.7 as foam velocity increases from 5 to 6-ft/sec. It can be noticed that when foam velocity is increased from 5 to 6-ft/sec, the decrease in fill gradient is almost half than foam flowing at 3 to 5-ft/sec. Also, reduction in the fill concentration is pronounced in the diameter ratio of 0.50. Slopes of fill concentration at different foam velocities are shown in Table 4.4.

Table 4.4: Gradient ($\partial C / \partial V$) of fill concentration at different foam velocities

Particle size (mm)	**Gradient at low foam velocities (3 to 5-ft/sec)**	**Gradient at high foam velocities (5 to 6-ft/sec)**
0.5	1.5	0.1
1	2	0.2
2	3	1.6
3	4.7	2.7

Effect of foam velocities on the fill concentration is shown in Figure 4.12. It can be noticed that at low foam velocity around 3 to 5-ft/sec there is a higher reduction in the fill concentration. At small size particles around 1 mm and less, there is insignificant change in the fill gradient at high foam velocity and a prominent change in the concentration is observed when particle size increase from 1mm. As the particle size increases than there is a continues decrease in the fill concentration at low as well as high foam velocity.

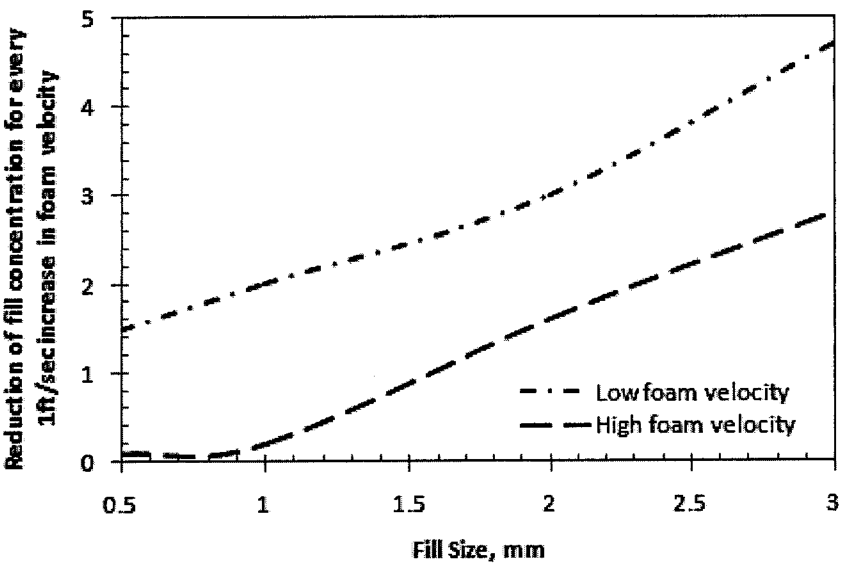


Figure 4.12: Fill gradient at high and low foam velocities

4.5.3 Effect of foam qualities on pressure drop

The relationship between the annular pressure drop and the quality of foam is presented as shown in Figures 4.13 (a) to 4.13 (d).In each case, analysis is carried out at constant fill size of 3 mm, diameter ratios from 0.35 to 0.50 and constant foam velocity. In all cases, there is appreciable increase in pressure drop as foam quality increases for a constant diameter ratio and foam velocity. However, this increase in pressure drop is not very significant especially at high foam quality. This phenomenon is attributed to the decline in fill concentration removal due to the increase in cuttings slip velocity as foam quality increases. Effect of foam quality on pressure drop is discussed in two different ways as given below;

4.5.3.1 Percentage increment in pressure drop

For instance, in Figure 4.13(a), for a constant diameter ratio of 0.35, pressure drop increases by 25% as foam quality increases from 70 to 80%. Conversely, only 5% decrease in pressure drop is recorded as foam velocity increases from 80 to 90%. Similar trends could be observed in Figures 4.13(b) to 4.13(d).

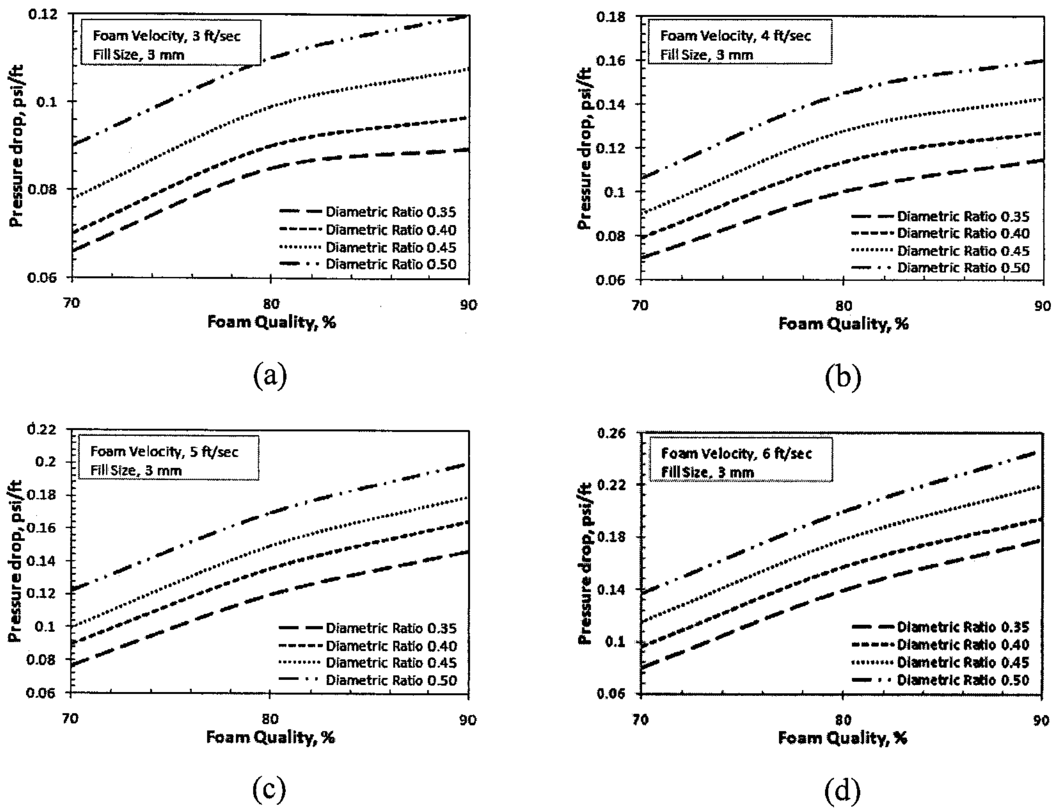


Figure 4.13: Effect of foam quality on pressure drop: (a) At foam velocity of 3-ft/sec, (b) At foam velocity of 4-ft/sec, (c) At foam velocity of 5-ft/sec, (d) At foam velocity of 6-ft/sec

4.5.3.2 Slope increment in pressure drop

At foam velocity of 3-ft/sec, there is significant pressure gradient around 0.002 when foam quality increases from 70 to 80%; however, when foam quality increases from 80 to 90%, an insignificant pressure gradient occurs as shown in above mentioned Figure 4.13 (a). As the foam velocity increases to 4-ft/sec, pressure gradient increases to 0.003 at 70 to 80% foam quality and pressure gradient reduces to

0.001 as the quality increases from 80 to 90% at foam velocity of 4-ft/sec as shown above in Figure 4.13 (b).

Above mentioned Figure 4.13 (c) also presents pressure drop as a function of quality at foam velocity of 5-ft/sec and different diameter ratios. At low foam quality, average pressure gradient is two time i.e. 0.004 of the average pressure gradient around 0.002 at high foam quality. Similarly, Figure 4.13 (d) shows the average pressure gradient has increased to 0.006 at low foam quality and it increased to 0.004 at high foam quality at 6-ft/sec. Slopes of pressure drop at different foam qualities are shown in Table 4.5.

Table 4.5: Gradient ($\partial P / \partial Q$) of pressure drop at different foam qualities

Foam velocity (ft/sec)	Gradient at low foam qualities (70-80%)	Gradient at high foam qualities (80-90%)
3	0.002	0.0001
4	0.003	0.001
5	0.004	0.002
6	0.006	0.004

Figure 4.14 shows that the pressure gradient for annular foam flow is high at low foam quality. It can be noticed that average increase in the slope is around three time with every 10% increase in foam quality. Also it is found that pressure drops in a sequence way with the increase of foam velocity. The difference in the slopes of low and high qualities foam is almost same at low and high foam velocities.

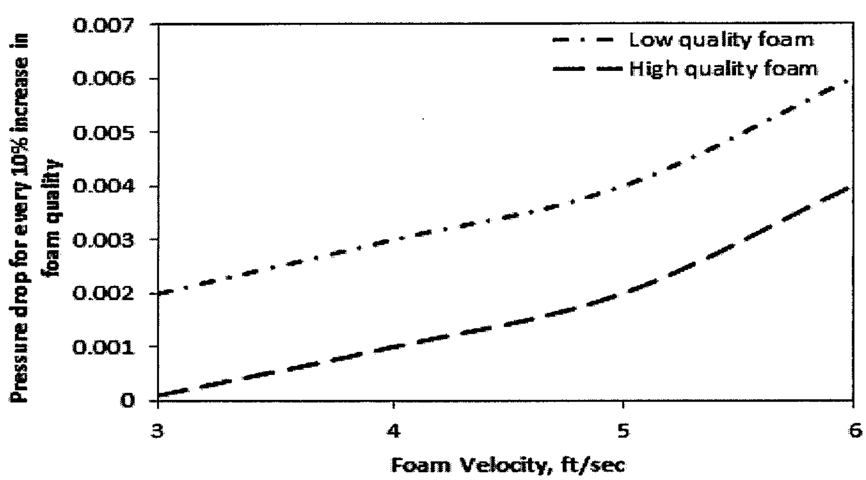
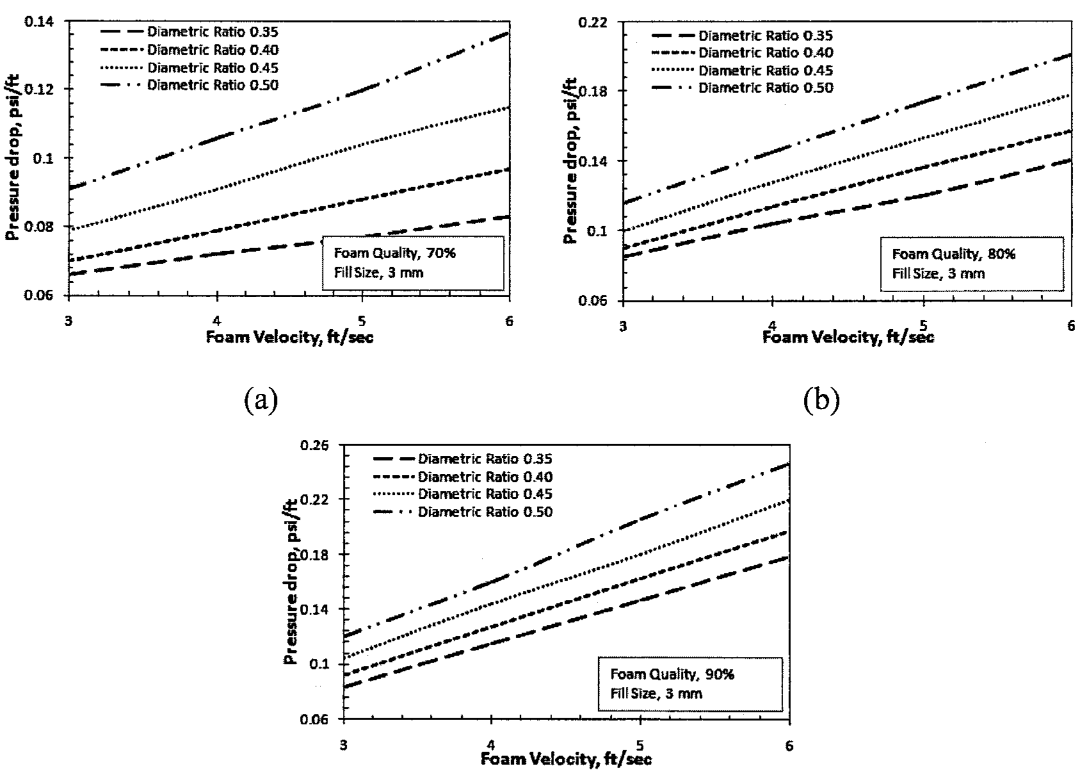


Figure 4.14: Pressure gradient at high and low foam qualities

4.5.4 Effect of foam velocities on pressure drop

In this section, the effect of foam velocity on annular pressure drop is discussed. Fluid velocity is known to be one of the major factors affecting cuttings transport. Figures 4.15 (a) to 4.15 (d) present the results at constant diameter ratios, foam quality and fill size. In all cases, an increase in foam velocity from 3-ft/sec to 6-ft/sec results in a dramatic rise in pressure drop at each constant diameter ratio. For instance, in Figure 4.15 (a) and a constant diameter ratio of 0.50, pressure drop increases by 10%, 11%, and 14% as foam velocity increases from 3-4 ft/sec, 4-5 ft/sec, and 5-6 ft/sec respectively. The pressure drop increment is almost constant as foam velocity also increases. Similar trends are also observed in Figures 4.15 (b) and 4.15 (c). Usually, an increase in fluid velocity results in an increase in the shear stress between the fluid and the pipe wall as well as cuttings. Since this shear stress is directly proportional to annular pressure drop, an increase in the latter will result in an increase in the former, and vice versa. Slopes of pressure drop at different foam velocities are shown in Table 4.6.



(c)

Figure 4.15: Effect of foam velocity on pressure drop: (a) At foam quality of 70%, (b) At foam quality of 80%, (c) At foam quality of 90%

Table 4.6: Gradient ($\partial P / \partial V$) of pressure drop at different foam velocities

Foam quality (%)	**Gradient at foam velocities (3 to 6-ft/sec)**
70	0.01
80	0.02
90	0.03

4.5.5 Effect of particle size on pressure drop

In the present study, a linear tendency for the pressure drop is noticed as particle size increases for all the CT/Annulus diameter ratios. The relationship between the annular pressure drop and the fill size is presented in Figure 4.16. Surprisingly, it is discovered that fill diameter has insignificant effect on pressure drop.

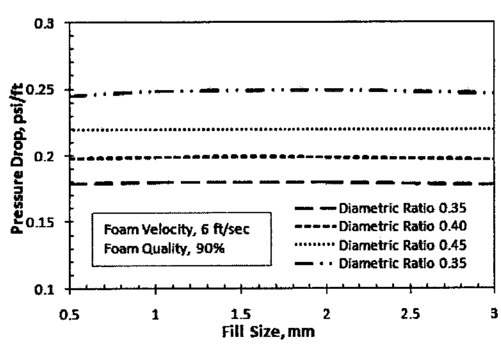
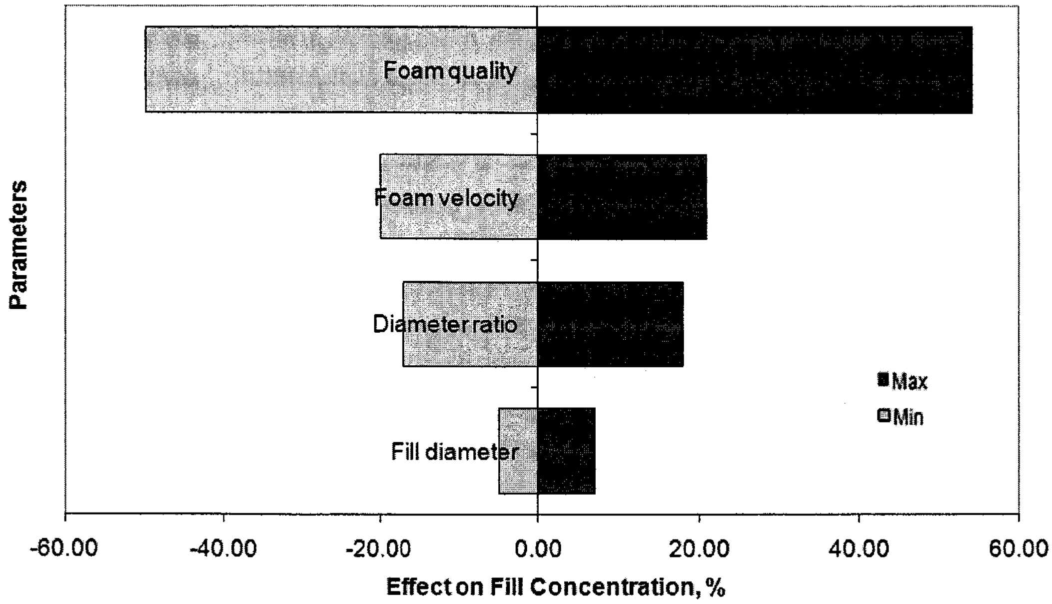


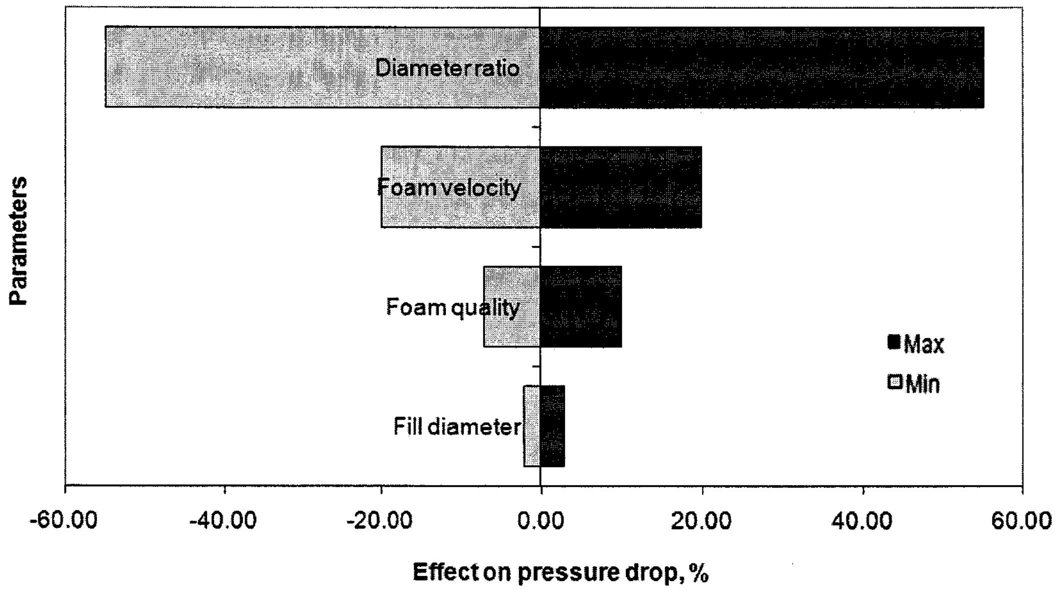
Figure 4.16: Effect of fill sizes on pressure drop

4.6 Factors affecting fill concentration and pressure drop

Figure 4.17 shows the influence of factors which effect the fill concentration and pressure drop. It has been found that influences of foam quality on fill concentration is more than foam velocity, diameter ratio and fill size as shown in Figure 4.17 (a). Present study shows that CT/Annulus diameter ratio has the most significant effect on the pressure drop. It can be also observed that foam velocity has significantly more effect on pressure drop as compared to foam velocity. Fill size has no significant effect on the pressure drop as shown in Figure 4.17 (b).



(a)



(b)

Figure 4.17: Parameters affecting fill concentration and pressure drop: (a) Effect on fill concentration, (b) Effect on pressure drop

4.7 Concluding remarks

Numerical model has been validated with the experimental and mathematical particle transport study with foam. Numerical results matched favorably with experimental results and hydraulic model. After validation of numerical model, fill concentration was calculated along the horizontal annulus for each quality of foam, by keeping the inner tubing stationary (no rotation). It was observed that foam flowing at 6-ft/sec results in the efficient cleaning of wellbore. In the present study, foam-solid transport was observed at three different foam qualities. It was found that particle transport is efficient at lower foam quality as compared to high foam quality. The analysis was performed by varying the particle size which ranges from 0.5 to 3 mm. It was observed that small particle i.e. 0.5 to 1 mm, can be removed effectively at 5-ft/sec foam velocity. At higher particle size around 2 to 3 mm, 6-ft/sec annular foam velocity is required to remove the particles. Coiled tubing cleaning operation was also studied by changing the CT/Annulus diameter ratios. It is observed that diameter ratio has a significant effect on the fill concentration when the foam quality is low i.e. between 70 to 80% quality foam. It is found that effect of diameter ratio on the fill concentration decreases when foam quality increases. As accepted, it is observed that diameter ratio has the significant effect on the pressure drop. The present study shows that the pressure gradient is higher at low foam quality as compared to higher foam quality. The effect of foam velocity on pressure drop was calculated. The results indicates that there is a linear increase in the pressure drop with the increase of foam velocity. The effect of particle size on the pressure drop was also calculated, it was discovered that particle size has no effect on the pressure drop.

CHAPTER 5

CONCLUSION AND RECOMENDATIONS

5.1 Conclusion

Present numerical study showed the foam-solid transport during coiled tubing cleanup operation which was expensive with experiment technique. Numerical model of foam-solid transport in the horizontal well was developed by considering operating scenario i.e. tubing has no rotation and it is penetrating in the solid surface at rate of 60-ft/hr. Three different qualities of foam were taken to observe the solid transport. The rheological characteristics of foam are taken from the previous experimental study. Numerical model is validated with the previous experimental study which was carried out at University of Tulsa. The results are compared with the experimental data as well as mathematical model. An agreement between numerical model and experimental data confirms the validity of model setup. Parametric study was extended by taking four different CT/Annulus diameter ratios. During the fill transport with foam, wall slip was ignored and also tubing is considered concentric in the annulus. During flow of each quality of foam an image of fill settlement is also taken at each different foam velocity. The effect of gravity is significant at low foam velocity. Following are achievements in the present study:

- Foam flow velocity specification is found for efficient transport of fill produced in the horizontal wellbore
- It is also found that solid particles concentration is more affected by the quality of foam as compared to velocity of foam.
- It is also discovered that low foam quality can clean the wellbore more efficiently as compared to high quality foam.
- CT/Annulus diameter ratio has less effect on the fill concentration as compared to foam quality and velocity.

- It is discovered that CT/annulus diameter ratios has considerable effect on the fill consideration when foam quality is low and it has insignificant effect as the foam quality increases.
- Pressure drop in the annulus increases with the increase of foam velocity, quality and diameter ratio.
- Diameter ratio has high impact on the pressure drop for annular foam-solid flow.
- It is also observed that fill particle size has no effect on the annular pressure drop.

5.2 Originality of work

The originality of research work is presented as follows:

- Herschel-Buckley viscosity model is used to specify the rheology of foam which is the combination of Power Law model and Bingham model.
- Different particles size was used to estimate the fill concentration.
- Present study is carried out by taking the effect of different diameter ratios of CT/Annuls on fill concentration and pressure drop.

5.3 Recommendations

The recommendations are suggested for further study as follows;

- The study can be further improved if more foam qualities are used.
- The study can be extended by including the effect of inclination and considering the eccentricity of coiled tubing for more accurate estimation of foam-solid transport.
- Longer and larger pipe systems would characterize the field conditions in a more realistic way.

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