Horizontal Well Cleanup Operation using Foam in Different Coiled Tubing/Annulus Diameter Ratios

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ABSTRACT

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. So, It is required to analyze a fluid which can suspend the solid particles even at low annular velocities and efficiently clean the wellbore. Recently, the use of foam as cleaning agent has become more popular due to its low density and high viscosity which are desirable in many underbalanced operations. This study is focused to analyze the coil tubing fill cleanout with foam in horizontal annulus. The objective of this paper is to investigate the effect of foam quality and velocity on fill concentration during horizontal wellbore cleanup operation at different CT/Annulus diametric ratios using Herschel Buckley viscosity model. Results showed that foam quality and velocity are the deciding factors for the fill transport. Present study also showed that for all size of fill particles, lower foam quality removes fill more efficiently than higher foam quality. It is noticed that diametric ratio has high effect on particle removal when foam quality is 70 %. Surprisingly, it is found that the effect of diametric ratio on fill concentration decreases when foam quality is 90%.

INTRODUCTION

Fill (cuttings, sand and fine) material left in the cased annulus reduces the production of wellbore. Therefore ,well cleaning operation is required to enhance the oil/gas production. Additionally, fill removal is necessary to permit the passage for operational tools and to remove the choking material for completion operations. Several techniques, such as dual string system, pump to surface bailing have been developed in the past. One of 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. Currently, fill removal is the largest CT application with approximately 50% of all CT operations industry wide (Li and Green, 2011).

Coil Tubing has two circulation modes to remove solid particles, namely the forward and reverse circulation modes as shown in Fig. 1. In the forward circulation mode, Cleaning fluid is pumped in the tubing and mixture of fill and foam is circulated back through cased annulus. On the other hand, reverse circulation is carried out by injecting fluid from cased annulus and circulated back through coiled tubing. Present study is focused on the forward circulation flow of the cleaning fluid.

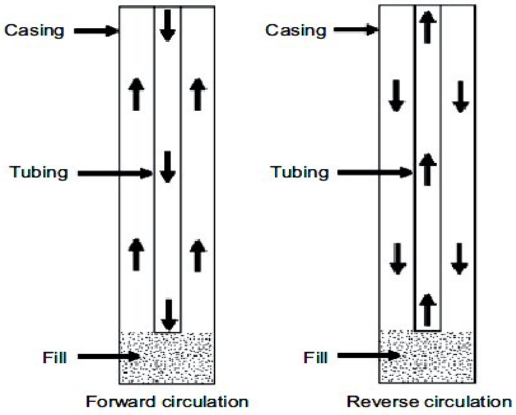

Figure 1: Two type of fill cleaning circulation mode (Li et al., 2010)

Fill removal operation is carried out by inserting coiled tubing in the cased annulus. Cleaning fluid is injected in the tubing from surface facilities which penetrates in the fill surface and circulate out the solids to the surface. In case of compact fill, high energy jets or drill bits run on motors can be used to break up the compactness and to take of the fill. The cleanout operation is carried out by continuous penetration of CT into the fill (Li and Green, 2011).

Solid particles transport is problematic in horizontal wellbore (Li and Luft, 2006) as shown in Fig.2. In this situation, fill particles drop down the lower side of annulus and form a solid bed. In practice, the velocity of circulation fluid in the annulus is kept greater than the settling velocity of the particle. This is to ensure that the circulation fluid has higher buoyancy force than the gravity force of solid particles. Selection of fluid is the important factor in designing the cleanout operations (Walton, 1995). To overcome the problem, study is forwarded to analyze the fill removal with foam along horizontal well. Foam fluid can be used in multiple BHP conditions. So foam treatments are also applicable in low and very low BHP conditions with very large wellbore. These are the most challenging conditions to transport solid particles from wellbore.

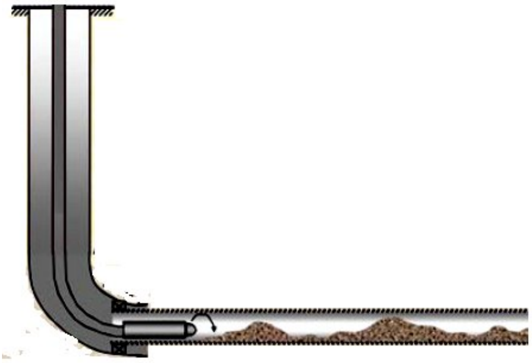

Figure 2: Fill removal from horizontal well (Li et al., 2008)

Presented in Fig.3 is a common equipment configuration for foam being used in the removal of fill. 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 (Li et al. 2010).

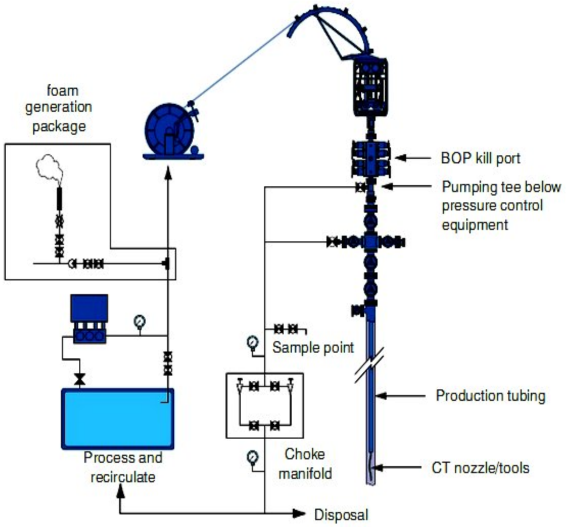

Figure 3: Typical foam equipment configuration for fill removal (Lane, 2005)

Literature review

In the last decade (Walker and Li 2000, Li and Walker, 2001 and Li et al. 2002) many fluids have been practiced to analyze the solid removal tests. These fluids includes Water, Xanvis and HEC gels. Following are the conclusion drawn from the previous studies.

The properties of cleaning fluid have a direct effect on the solid particle transport. It was observed that shear forces at the solids surface and fluid interface contribute a main role in the solids removal. Hence, the fluid flow behavior and hole to tubing diametric ratio have the dominating effect on the fill transport. It has been also concluded that well cleaning is efficient with low viscosity fluid with high flow rates. Previous studies show that the solids transport dependents upon the rheological behavior of the fluid. It has been observed that Xanvis and HEC polymer based fluids has high suspension than water but unable to erode the packed surface of stationary fill bad. It has been noticed that circulation of the cleaning fluid is limited to low flow rate in the coiled tubing. Therefore, it is not possible to achieve the in-situ velocity of circulation fluid in casing that is high enough to overcome the particles deposition velocity. Present study aim is to investigate the fill transport with foam during horizontal well cleanup operation.

Walker and Li (2000) studied experimentally that the particle size and fluid rehology 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 .76mm are difficult to remove.

Herzhaft et al. (2003) experimentally studied that solid transport efficiency increases with high quality of foam. Li and Kuru (2003) incorporated a model for hydraulic calculations of cutting transport with foam during horizontal wellbore drilling operation. They found a relation for the critical velocity of foam to transport the drill cuttings. They analyzed that cuttings efficiency increases at higher foam flow rate. Li and Kuru (2004) concluded that critical velocity of foam has no effect of temperature variation between $30^{\circ}C$ and $100^{\circ}C$. Loureno et al. (2003) also verified experimentally that rehology of foam has no influence of change in temperature.

Bailey et al. (2006) studied the slurry flow which composed of gel and sand at reel to injector section of coiled tubing. They found that pressure gradient remains consistent and linear from reel to injector section. They founded that the increase or decrease in the curvature of tubing reel has no effect of pressure gradient.

Li et al. (2010) formulated the effect of temperature and pressure on the velocity of foam in the vertical wellbore. They concluded that in vertical well cleanup operation, the velocity of foam fluid should be according to following equation:

$$V_F \geq 1.1 V_t \tag{1}$$

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

where, V_t is the terminal velocity, D_s is the diameter of sand particle, ρ_S is the density of sand , ρ_F is the density of foam and n is the exponent.

In the past, drilling cuttings transport with foams has been studied along the horizontal wellbore, study has forwarded to understand the fill transport with foam along horizontal wellbore during coiled tubing cleanup operation. Recently, Khan and Pao (2013a, 2013b) reported that well cleaning can be achieved with lower quality of foam as long as its circulating velocity is high i.e. 6-ft/sec. They also observed that sand settled down at bottom of annulus and form continues bed when the annular velocity is less than 5-ft/sec. They concluded that fill concentration in the annulus is mostly dictated by foam quality rather than its velocity. They also found that pressure loss increases with the increase in the foam quality.

METHODOLOGY

In the present study, ANSYS-CFX-14 is used to analyze the fill removal from horizontal wellbore using foam as a cleaning fluid. Bailey et al. (2006) also used this method to investigate the pressure gradient of non Newtonian slurry composed of gel and sand at reel to injector section of coiled tubing. Similar approach has been used by Bilgesu et al. (2002) to investigate the cutting transport efficiencies in vertical well.

In this numerical study, the flow is assumed to be in pseudo-steady state condition. Analysis is performed by keeping coiled tubing fully concentric in the annulus. Outer wall of coil tubing and inner wall of casing are assumed to be smooth i.e. there is no friction. Herschel-Bulkely model is assumed for the viscosity calculation of water based foam. Following is the rheological relation of foam

$$\tau = \tau_0 + K\gamma^n \qquad (3)$$

where, τ is the shear stress, τ_0 is the yield stress, K is the consistency index, γ is the shear rate and n is the power index for non-Newtonian fluid.

Herschel-Bulkely viscosity model parameters for water base foam was analyzed by Miska et al. (2003) as shown in Table 1, and their values are assumed valid in the present study.

Table 1: Rheological Model Parameters

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

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 are varied from 3-6 ft/sec, are applied at annulus inlet. The rate of penetration of tubing inside the fill is taken 60 ft/hr. Particle shape is spherical having average diameter of 3mm. There is a uniform injection of fill particles at annulus inlet. Injection flow rate of solid particles are calculated using following equation.

$$Q = \rho VA \qquad (4)$$

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.

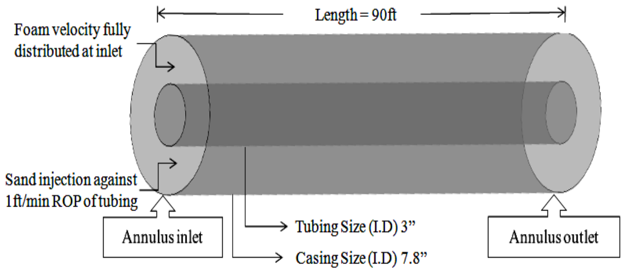

Figure 3: Schematic well diagram.

Particle transport multiphase model was chosen to calculate the mass fraction of the fill particles along the annulus. In this model fill particles are taken as fully distributed in a continuous foam phase. All the particles were tracked, starting from the area of injection until the exit area of fill particle throughout continues foam phase. The track of particle was carried out by formulating a set of regular equations in time for each fill particle. These final equations were then integrated by proceeding with a simple integration scheme for the calculation of each particle movement in the foam phase. In the present study, rotational force is involved to validate the numerical model with experimental data because inner pipe rotation was involved in the flow loop test. The rotational force causes the rotation of fluid domain which effects the suspension of the solid particles.

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

$$x_i^n = x_i^o + v_{pi}^o \delta t \qquad (5)$$

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. The particle velocity is defined as

$$v_p = x_f + (v_p^o - v_f)\exp(-\frac{\delta t}{\tau}) + \tau F_{all}\left(1 - \exp(-\frac{\delta t}{\tau})\right) \tag{6}$$

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

The forces which acted on the particle are drag (F_d), buoyancy (F_b), lift (F_l) and virtual mass forces (F_{vm}) to analyze the settlement of the particles are defined as

$$m_p \frac{dUp}{dt} = FD + FB + FP + FR \tag{7}$$

where, m_P is the mass of the solid particle, dUp/dt is the particle velocity and FD is the drag force acting on the particle, FB is the buoyancy force, FR is the force due to tube rotation and FP is the pressure gradient.

$$\mathrm{F_D} = 1/2\mathrm{C_D}\rho_\mathrm{F}\mathrm{A_F}|\mathrm{U_S}|\mathrm{U_S} = 1/2\mathrm{C_D}\rho_\mathrm{F}\mathrm{A_F}|\mathrm{U_F} - U_P|(\mathrm{U_F} - \mathrm{U_P}) \tag{8}$$

$$\mathrm{F_B} = (\mathrm{m_P} - m_F)\mathrm{g} = \mathrm{m_P}(1 - \frac{\rho_\mathrm{F}}{\rho_\mathrm{P}})\,\mathrm{g} = \frac{\pi}{6}\mathrm{d_P^3}(\rho_P - \rho_\mathrm{F})\mathrm{g} \tag{9}$$

$$\mathrm{F_P} = \frac{m_\mathrm{F}}{\rho_\mathrm{P}}\nabla \mathrm{p} \tag{10}$$

$$\nabla \mathrm{p} = \left(\frac{\partial \mathrm{p}}{\partial \mathrm{x}} + \frac{\partial p}{\partial y} + \frac{\partial p}{\partial z}\right) \tag{11}$$

$$\mathrm{F_R} = \mathrm{m_P}(-2\Omega \times U_P - \Omega \times \Omega \times r) \tag{12}$$

where, C_D is the drag coefficient, A_F is the area of the particle , U_S is the slip velocity, U_P is the particle velocity, ρ_F is the density of foam, ρ_P is the density of particles and r is the location vector.

RESULTS AND DISCUSSIONS

In the previous study Khan and Pao (2013), verified a numerical model with the experimental study which was carried out by Chen et al. (2007). It was noticed that the decrease in particles concentration was almost matching with the experimental study. It has been verified that the numerical model is set for the parametric study of fill transport with foam during coil tubing cleanup operation. Numerical analysis was carried out by using following parameters as shown in Tab. 2

Table 2: Parameters for simulation

Foam quality (%)	Foam velocity (ft/sec)	Fill diameter (mm)	Diameter ratios (CT/Annulus)
70	3, 4, 5, 6	0.5, 3	0.35, 0.4, 0.45, 0.5
80	3, 4, 5, 6	0.5, 3	0.35, 0.4, 0.45, 0.5
90	3, 4, 5, 6	0.5, 3	0.35, 0.4, 0.45, 0.5

A. *Effect of quality when particle size is small*

In the present study, a decreasing trend for the fill concentration is noticed as fluid quality increases for all CT/Annulus diametric ratio. 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 Figure 4. It can be noticed that for all particles sizes, lower foam quality removes fill more efficiently than higher foam quality. A decreasing trend for the fill concentration is noticed as fluid quality increases for all of the CT/Annulus diametric ratios and fill sizes.

It shows the percentage decrease of fill for 0.5 mm particle size when foam quality varies from 70 to 90%. There is 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 -0.38 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 diametric ratio has high effect on particle removal when foam quality is 70%. Surprisingly, it is found that the effect of diametric ratio reduces when foam quality is 80% or above.

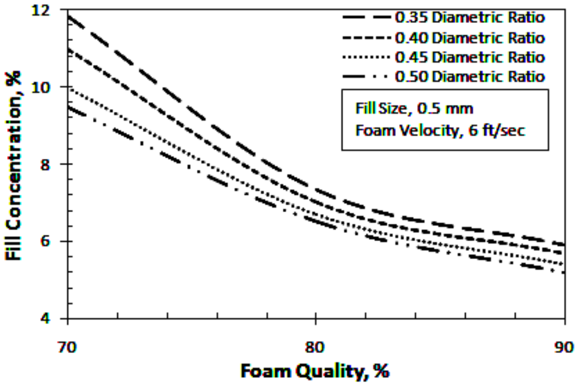

Figure 4: Effect of foam qualities on small particle size

B. *Effect of quality when particle size is large*

Figure 5 shows the percentage decrease of fill for 3 mm particle size when foam quality varies from 70 to 90%. Average fill gradient calculated -0.51 at low foam quality and it reduces to -0.24 when foam quality increase from 80 to 90%. As the particle size is large so foam flowing at 6 ft/sec has less effect as compared to small size particles. Chen. et al [19] also found in their study that low foam quality is more efficient to remove solid particles as compared to high foam quality.

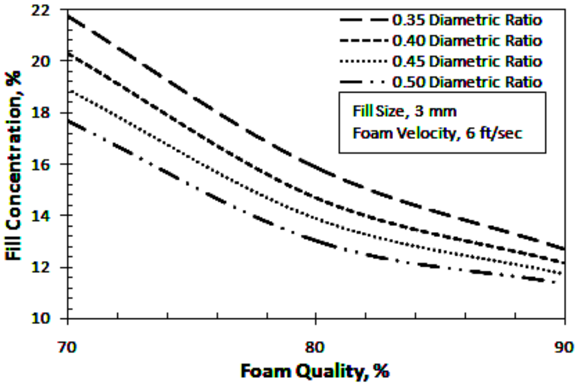

Figure 5: Effect of foam qualities on large particle size

C. *Effect of velocity when particle size is small*

In all of the studies, a decreasing trend for the fill concentration is noticed as fluid velocity increases for all of the CT/Annulus diametric 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 Figure 6.

It shows the fill concentration of 0.5 mm size in the annulus vs. foam velocities of 90% foam quality at different CT/Annulus diametric ratios. The maximum fill concentration is 9% and it occur for foam flow at 3 ft/sec in CT/Annulus diametric ratio of 0.35. The lowest fill concentration is 5% and it occurs for foam flowing at 6 ft/sec in CT/Annulus diametric ratio of 0.5. It can be noticed from the graph that as the foam velocity increases from 3 to 5 ft/sec, there is a linier trend that fill concentration decreases. 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.

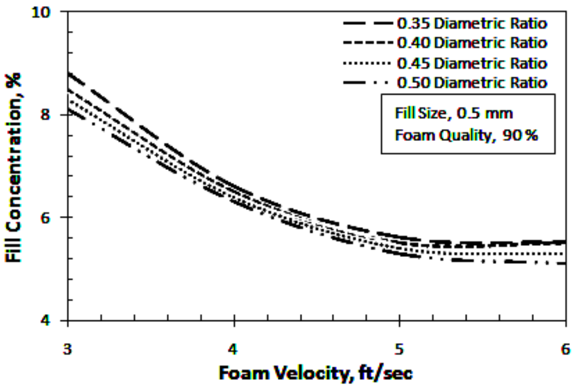

Figure 6: Effect of foam velocities on small particle size

D. *Effect of velocity when particle size is large*

Figure 7 shows fill concentration of 3 mm particle size in the annulus vs. foam velocities of foam quality 90% at different CT/Annulus diametric 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 diametric ratio of 0.50 as the foam velocity increase from 3 to 6 ft/sec, concentration reduces from 23 to 12%.

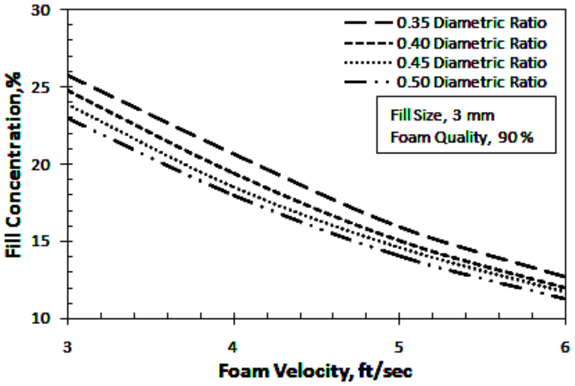

Figure 7: Effect of foam velocities on large particle size

CONCLUSION

This research concluded that fill concentration decreases proportionally to fill diameter. Also, decreasing trend for the fill concentration is noticed as fluid quality and velocity increases for all of the CT/Annulus diametric ratios Surprisingly, it is discovered that diametric ratio has significant effect for the removal of large size particles as compared to small size of particles. It is found that the quality of foam has significant effect on fill concentration. Fill removal has better performance with foam of low quality at annular velocity of 6ft/sec.

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