Jurnal Teknologi

Full paper

Improving Gas Bubbles' Half Life in Foam Drilling Fluid

Issham Ismail[a*], Nur Suriani Mamat[a], Mohd Baihaqi Mamat[b], Ahmad Shamsulizwan Ismail[a], Azmi Kamis, Azman Ikhsan[a]

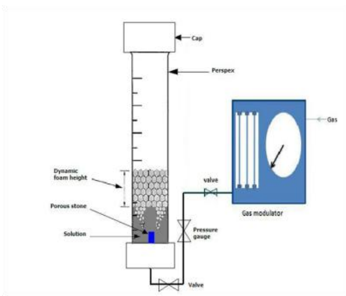
[a]*Faculty of Petroleum & Renewable Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*
[b]*Geowell Sdn. Bhd., 151, Jalan Aminuddin Baki, Taman Tun Dr. Ismail, 60000 Kuala Lumpur, Malaysia*

*Corresponding author: issham@petroleum.utm.my

Article history

Received :11 September 2012
Received in revised form :
21 February 2013
Accepted :15 April 2013

Graphical abstract



Abstract

An underbalanced drilling using foam drilling fluid is one of the most effective solutions which are capable of preventing formation damage, differential sticking, or circulation lost. Nevertheless, the limitation of using foam drilling fluid is the stability of its rheological properties which would affect its lubricity characteristics. Therefore, a research study was carried out to determine the stability and effectiveness of water soluble polymers as an additive in foam drilling fluid. To produce the required and most stable foam, four types of surfactants had been tested, namely sodium dodecyl sulfate (anionic), cetyltrimethylammonium bromide (cationic), T×100 (non ionic), and *n*-alkyl betaines (amphoteric). Then, the water soluble polymers, namely xanthan gum, hydroxyethyl cellulose, guar gum, and carboxymethyl cellulose, were evaluated as a stabilizer in the said foam drilling fluid. The laboratory works involved lubricity and rheological properties tests, which were conducted at ambient condition. The experimental results showed that the use of xanthan gum with anionic surfactant produced the most stable foam drilling fluid compared to other polymers. Rheological properties of the polymer foam drilling fluid were compared with water-based mud, and it was revealed that polymer foam drilling fluid could perform as effective as the latter. The significant advantage of using polymer foam drilling fluid was its coefficient of friction which was found to be lower than the water-based mud.

Keywords: Foam drilling fluid; foaming agent; surfactant; underbalanced drilling; water soluble polymer

Abstrak

Penggerudian imbang bawah menggunakan bendalir busa gerudi ialah satu daripada penyelesaian yang paling berkesan bagi mencegah daripada berlakunya kerosakan formasi, lekatan pembezaan, dan kehilangan edaran. Walau bagaimanapun, batasan dalam penggunaan bendalir busa gerudi adalah tentang kestabilan sifat-sifat reologinya yang boleh menjejaskan ciri-ciri kelinciran. Sehubungan dengan itu, suatu kajian telah dilaksana bagi menentukan kestabilan dan keberkesanan polimer larut air sebagai bahan tambah dalam bendalir busa gerudi. Bagi menghasilkan busa yang diperlukan dan busa yang paling stabil, empat jenis surfaktan telah diuji, iaitu natrium dodecil sulfat (anionik), cetiltrimetilamonia bromida (kationik), T×100 (bukan ionik), dan *n*-alkil betaine (amfoterik). Seterusnya, polimer larut air yang terdiri daripada gam xantan, hidroksietil selulosa, gam guar, dan karboksimetil selulosa, telah dinilai kesan masing-masing terhadap kestabilan bendalir busa gerudi terbabit. Kajian yang dilakukan di makmal melibatkan uji kaji sifat kelinciran dan uji kaji sifat reologi bendalir busa gerudi. Keputusan uji kaji menunjukkan bahawa penggunaan secara bersama gam xantan dengan surfaktan anionik berjaya menghasilkan bendalir busa gerudi yang paling stabil berbanding polimer yang lain. Sifat-sifat reologi bendalir busa polimer gerudi telah dibandingkan dengan lumpur dasar air, dengan keputusan uji kaji menunjukkan bahawa bendalir busa polimer gerudi boleh berfungsi sebaik lumpur dasar air. Kelebihan bendalir busa polimer gerudi ialah pekali geserannya yang lebih rendah berbanding lumpur dasar air.

Kata kunci: Bendalir busa gerudi; agen busa; surfaktan; penggerudian imbang bawah; polimer larut air

1.0 INTRODUCTION

Directional drilling is the practice of deviating a wellbore along a planned target at a given lateral distance and direction from the vertical. It is interesting to note that directional drilling has now become an imperative element in oil or gas field development, definitely for both offshore and onshore. Many problems and conflicts can be avoided by applying directional drilling, but drag and torque remains one of the main issues. Generally, drill string drag is the incremental force encountered when moving pipe up or down in the hole whilst torque arises from the pipe rotation [1]. Horizontal drilling increases the contact of the drill string with the borehole which will lead to friction problem. The combination resistance of drill string in the bend and the force gravity will increase the drill string's pressure to borehole contact. This may cause weight stacking, torque and drag, stickiness, low penetration rate, and even stuck pipe in the severe instances. Experience on some directional drilling operations has led to the development of many torque and drag reducing products and techniques [2]. For example, a novel fibrous lost circulation material was found to dramatically reduce torque and played a major part in the successful of drilling of oil wells at Wytch Farm and Tierra Del Fuego [3].

The fundamentals of drilling horizontal wells include underbalanced drilling (UBD), coiled tubing, bit steering, continuous logging (measurement-while-drilling), multilateral and horizontal completions. Underbalanced drilling is a non-conventional drilling operation where the hydrostatic pressure of the drilling fluid is maintained below the formation pore pressure. The benefits of UBD include increased productivity by reducing formation damage, increased rate of drilling bit penetration, minimization or elimination of lost circulation, improved formation evaluation while drilling, reduction or elimination of differential pipe sticking, reduced stimulation requirements, and earlier production [4]. Among the existing low-density fluids used in underbalanced drilling, foam is very beneficial due to its encouraging cuttings carrying capacity. Foam [5] comprises a mixture of gas phase and foaming solution, is one of the most versatile aerated fluids. It allows the use of very low specific gravity from 0.2, and is one of the most efficient fluids for lifting the cuttings and cleaning the wellbore. However, the knowledge of foam properties and especially the flowing properties is still incomplete. Foam rheology has been the subject of numerous investigations in the past [6, 7, 8, 9]. Thus, this research work was conducted to study the rheology and lubricity of drilling foam. Typically, drilling foam is thermodynamically unstable with a complex rheology, containing 5-25% liquid with not more than 95% of gas. As a result, despite a pseudo-stability initially exhibited, it eventually breaks down to its individual constituent phases. This break down is usually attributed to the gravitational drainage of liquid through the lamellae surrounding the foam cells. This aspect leads to gradual thinning and eventual rupture of the foam bubbles, or a decrease in surface area and consequently in surface energy occurring with the breakdown of a dispersed system.

Foam is one of the most widely used drilling fluids. Apart from generating a very low Equivalent Circulation Density (ECD), it also has good lubrication properties and hole cleaning capacity. As highlighted earlier, foam is a thermodynamically unstable fluid and its rheology is more complex [10]. Thus, the selection of suitable foaming agent is very important to maintain the stability of foam. Foam structure is best preserved through the use of an effective surfactant which enables the formation of stable interfacial surfaces. This effort should be coupled with the chosen of a suitable viscosifier which will reduce the rate of foam break mechanism, which has become the focus of this research work.

Foam stability is an important parameter to be considered seriously when foam is used as a drilling fluid in an underbalanced drilling. The foam stability is evaluated based on its half life. The presence of the electrolytes is found to have increased the surface tension of water and thus it will require high surfactant concentration to generate foam. Meanwhile the monovalent cations have the ability to create larger foam volume with larger bubble size than divalent cations. It is important to note that surfactants can lower surface tension and promote foam formation. Lowering the surface tension alone may create stable foam – important factors for foam stability are film drainage, which is in part controlled by bulk and surface viscosity, resistance to mechanical disturbances and the ability to counteract film thinning: both factors are governed by film elasticity. Aqueous solutions with lower surface tension produce larger volumes of foam with equal bubble size. The thin film, surrounding gas, must possess the elasticity and mechanical integrity necessary to maintain foam stability. The presence of aqueous solution of surfactant facilitates the stretching of the film [5, 11].

■2.0 MATERIALS AND EXPERIMENTALS PROCEDURES

2.1 Materials

Foaming agents (surfactants) used in this research works were anionic, cationic, amphoteric, and non ionic. The details of foaming agent, stabilizer, and salt used are shown in Table 1 whilst Figure 1 shows the schematic diagram of the experimental system. All the experimental works were conducted at ambient condition.

Table 1 Surfactants, stabilizers, and salt used in the research works

Surfactant (foaming agent)		Stabilizer		Salt	
(1)	Sodium dodecyl sulfate (anionic)	(1)	Xanthan gum	(1)	Sodium chloride
(2)	Tx100 (non ionic)	(2)	Carboxymethyl cellulose		
(3)	*n*-alkyl betaines (amphoteric)	(3)	Hydroxyethyl cellulose		
(4)	Cetyltrimethylammonium bromide (cationic)	(4)	Guar gum		

2.2 Foaming Generation

Foam formulation for this solution was the combination of tap water, 1% v/v of surfactant, and nitrogen gas. Nitrogen gas was bubbled at the bottom of the perspex with a constant rate of 60 ml/min into the 100 ml foaming solution. Bubbling was continued until the volume of foam achieved the maximum volume in the perspex. Time taken for the half of volume drainage from its initial volume was measured using a stop watch. The steps were repeated using different types of surfactant.

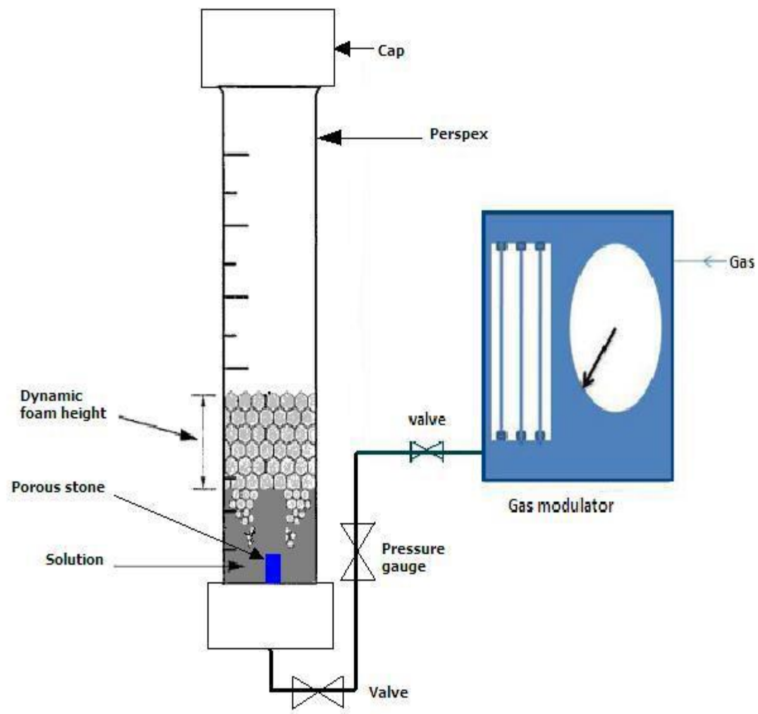


Figure 1 Foam generation model (air expansion technique)

2.3 Stabilizer

The water soluble polymer – used as a stabilizer in the foam drilling fluid – was evaluated in order to observe its effect on the stability of foams generated. Foam stability was examined by adding these additives to the aqueous phase in order to enhance viscosity and stability of the foams. The concentration of stabilizers was kept constant at 0.13% v/v. These additives were added into the 1% v/v solution of foaming agent that had been selected previously which indicated the highest stability when tested with the different foaming agents.

After the most effective stabilizer which resulted to the most stable foam has been identified, the test was continued with different concentrations of stabilizer that had been determined previously. The concentrations of stabilizer tested were 0.1%, 0.13%, 0.17%, and 0.2% (by volume) with the concentration of surfactant was kept constant at 1% v/v concentration. The longer half life indicated that it was the more stable with the addition of certain concentrations of stabilizer.

2.4 Salt

Another important aspect that should be analyzed was the ability of a foaming agent to keep foam stable in the presence brine in foam drilling fluid. In this research work, the foaming agent was tested using different concentrations of sodium chloride (NaCl) in the liquid phase. The concentrations of NaCl used were 2.3%, 4.6%, 6.9%, and 9.3% (by volume).

2.5 Lubricity Test

The lubricity of the foam drilling fluid was measured using the Fann Lubricity Tester, Model 212 EP/Lubricity Tester. Details of the experimental procedures are given in [12]. The instrument was set at 60 RPM and a pressure of 100 lbs. The lubricity can be calculated as follows:

$$\text{Coefficient of friction} = \frac{\text{Torque reading}}{100}$$

2.6 Rheological Properties

The rheological properties of foam drilling fluid were measured using a rheometer and was carried out as per the *American Petroleum Institute RP –13B –1*: *Recommended Practices for Field Testing Water-based Drilling Fluids* [13]. While the alkalinity of the foam drilling fluid was measured using a standard pH meter.

■3.0 RESULTS AND DISCUSSION

3.1 The Performance of Foaming Agent

Figure 2 shows the performance of each surfactant that was used in the research works to determine the stability of foam drilling fluid with different types of foaming agent. From the half life analysis, sodium dodecyl sulfate (SDS) and cetyltrimethylammonium bromide (CTAB) were found to have exhibited longer half life as compared to Tx100 and and *n*-alkyl betaines. This is due to the stabilization mechanism of anionic and cationic surfactant which was resulted from the molecular interactions forces (i.e., electrostatic repulsion in the double layer) [10]. The affinity of the ions for the air/water interface and the direct interaction of the ions with the surfactant do affect the stability and thickness of foam films [14].

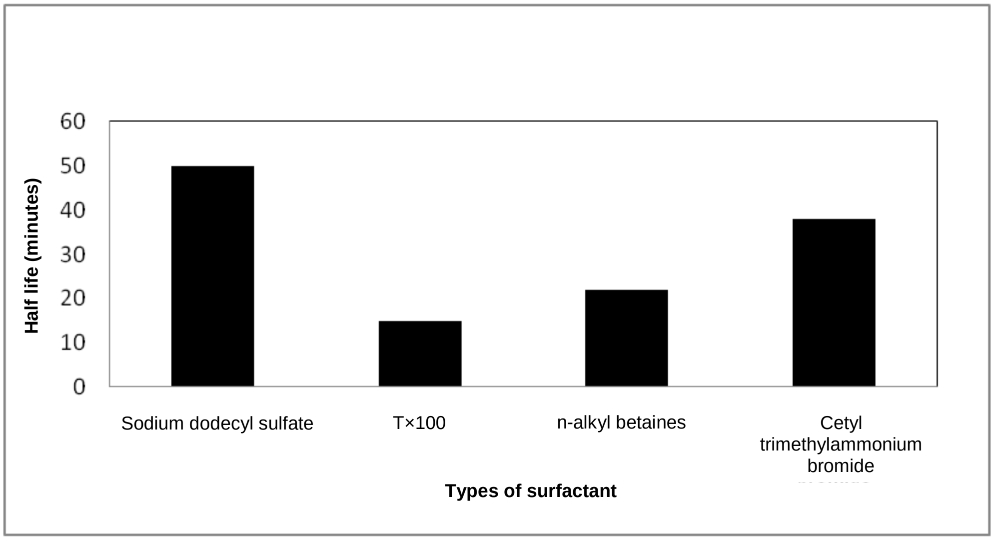


Figure 2 Effect of different foaming agents on stability of foam drilling fluid

3.2 Types of Additive

Water soluble polymers can stabilize foams by increasing the bulk viscosity of the film, thus it increases the film elasticity or decreases the film drainage rate. They are often effective at lower concentrations than other organic additives, and more compatible with different types of foaming systems [11].

The research works involved the evaluation of the effect of those four additives on sodium dodecyl sulfate that has been proved to have given the longest half life as compared to cetyltrimethylammonium bromide, Tx100, and *n*-alkyl betaines. The 1% v/v surfactant was mixed with water as liquid phase, and then the 0.13% v/v of additive was added into the solution. Nitrogen gas was injected into the solution to produce the said foam. Types of stabilizer that were used in the research works consisted of xanthan gum (XC), carboxymethyl cellulose (CMC), hydroxyethyl cellulose (HEC), and guar gum.

When surfactants are mixed in solution with other components, several bulk and interfacial properties change as compared to those of the single surfactant solution. In particular, the stability of foams is affected by three mechanisms: drainage, coarsening, and film rupture [15]. Generally, water soluble polymer would decrease micellar stability, and this phenomenon could increase the foamability of the mixed polymer-surfactant solutions. At higher surfactant concentrations, the bulk and surface viscosity are significantly increased, and again the foam stability increases [16].

Figure 3 shows that the foam solution after being mixed with 0.13% v/v xanthan gum produced very stable foam with half life of 214 minutes compared to other stabilizers. It could be said that the addition of polymer has succeeded in altering the bulk viscosity of the solution and other parameters which are related to solubility and diffusivity of gas introduced into the liquid phase.

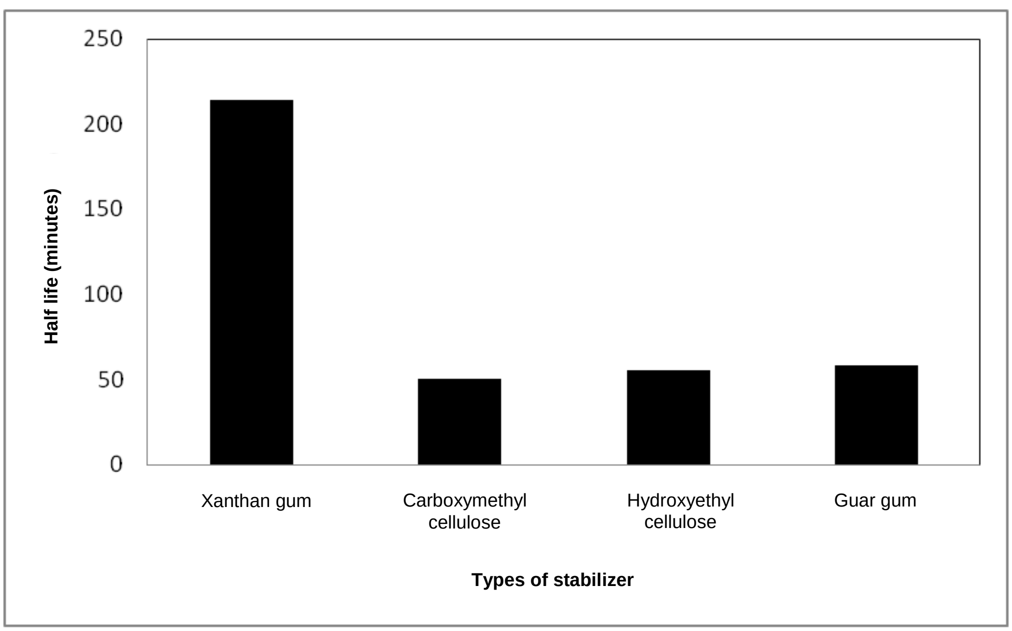


Figure 3 Effect of different additives on foam drilling fluid

3.3 Additives Concentration

The most common pattern of behavior for polymers and surfactants was for the surfactant to form micelles on the polymer chain at a concentration below the critical micelle concentration of the surfactant. This has changed the conformation of the polymer chain in solution, by a large amount if the surfactant was charged because it endowed the polymer with polyelectrolyte qualities. This alone would cause major changes to the rheological properties. The surfactant micelles might also cross-link the polymer molecules and the resulting gel-like structure which made the solution very viscous [17].

Figure 4 shows the experimental results of half life for foam drilling fluid tested with different concentrations of xanthan gum. Generally, when the amount of the polymer added is increased, the foam stability also would increase. As highlighted earlier, the addition of polymer has succeeded in altering the solubility and diffusivity of gas in the liquid phase. Both solubility and diffusivity of gas in the lamella liquid decreased as the liquid became more viscous due to the introduction of polymer. Such a decrease in these parameters reduced the permeability of the lamella. Consequently, the rate of inter bubble gas diffusion decreased. As a result, the rate of disappearance of smaller bubbles was found to have decline [17].

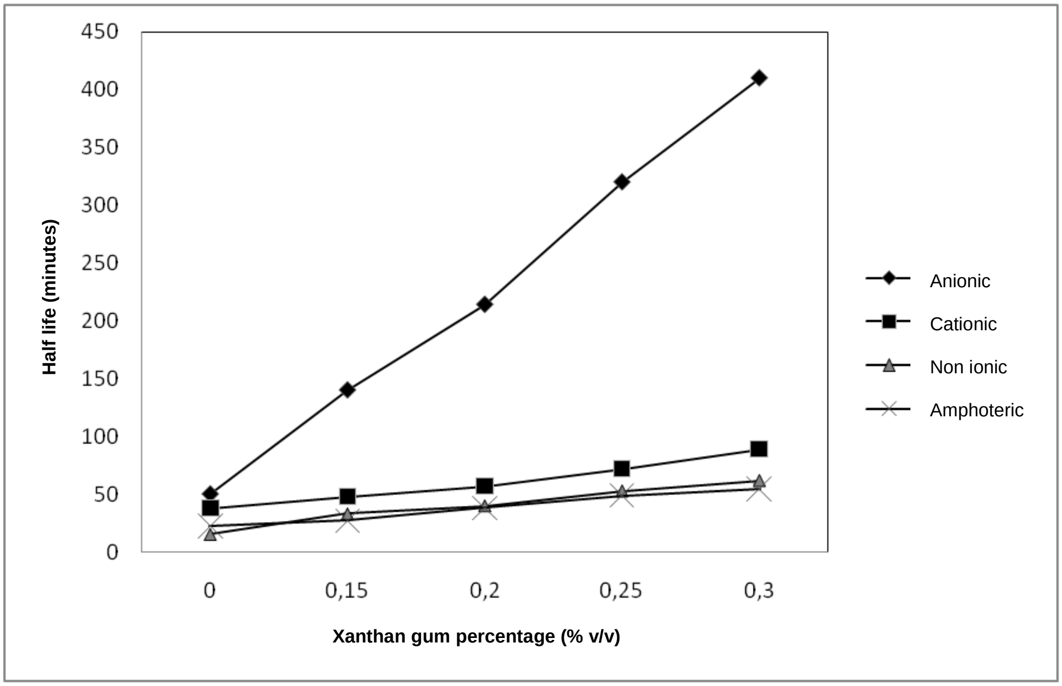


Figure 4 Half-life for foam drilling fluid with different percentages of xanthan gum

Another mechanism that can be related to the addition of xanthan gum into foam solution is the increase of mechanical strength of foam films. The surface films produced by solutions of highly purified surfactants often weakly coherent, containing molecules that are widely spaced because of the mutual repulsion of the oriented polar heads. These films are mechanically weak and non viscous. When they constitute the interfacial film in the lamellae of foam, liquid drains rapidly from the lamellae. The addition of this polymer to this type of film can convert it to a closer packed, more coherent one of high surface viscosity, which is slow draining and produces a much more stable foam [17].

3.4 Salt Concentration

Stability of foam in the presence of electrolytes contamination is an important parameter for foam drilling fluid. The sensitivity to salt is relying on the surfactants chemistry on the foaming system. During foam formation, it should be noted that surfactant molecules adsorb at a freshly created air/water interface from the bulk. The properties of a monolayer of surfactant, which is a good indicator of foam stability, are sensitive to the concentration and nature of the salt [18].

This research works also comprised the evaluation of monovalent salt effect of different concentrations on the stability of foams. To be more specific, sodium chloride (NaCl) has been chosen as it is abundantly present in the formation. This salt was tested on the foam drilling fluid with 0.2% v/v xanthan gum. Figure 5 shows the effect of different salt concentrations on the stability of foam drilling fluid. When the concentration of NaCl increased, the stability or half life of foam also increased. However, the stability of foam generated with the anionic surfactant reduced considerably after the addition of NaCl. The presence of NaCl in the solution has changed the concentration and viscosity of foam drilling fluid. Consequently, it increased the drainage rate from the lamellae of foam.

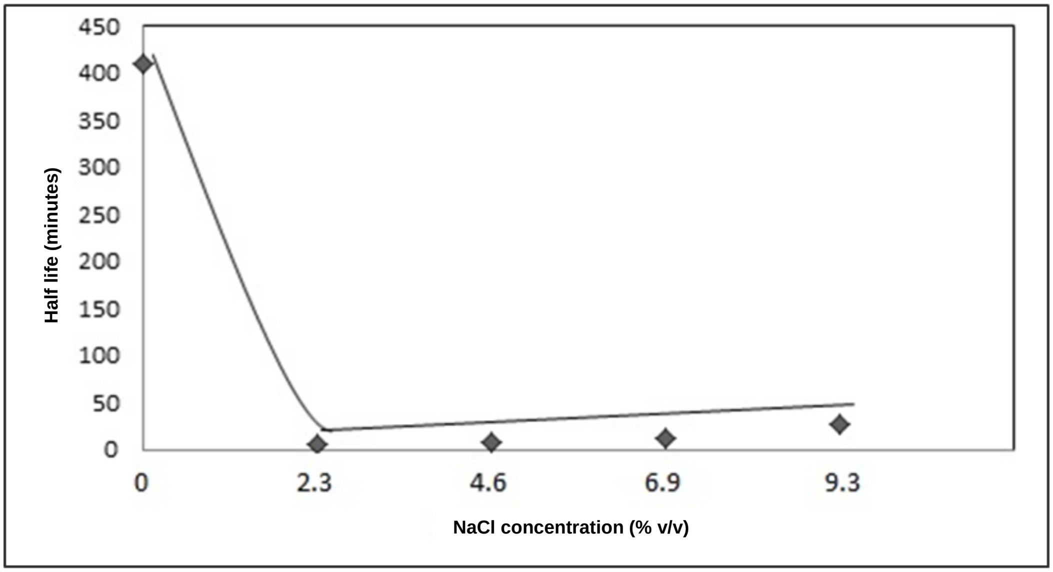


Figure 5 Effect of sodium chloride concentration on foam's half life

3.5 Coefficient of Friction

Figure 6 shows the trend of coefficient of friction for different types of mud. All of the values were obtained after being tested for three minutes. Water-based mud shows the highest reading of coefficient of friction, i.e., 0.275. However, foam drilling fluid shows a lower reading of 0.262 compared to water-based mud. The addition of 0.2% v/v xanthan gum shows further reduction of coefficient of friction to 0.239 (i.e., a 9.2% reduction from the basic foam drilling fluid). This means that the presence of the water-soluble polymer (i.e., xanthan gum) has succeeded in reducing the coefficient of friction. Hence, from the experimental works, it proved that introduction of 0.2% v/v xanthan gum into foam drilling fluid was able to act as a friction reducer in a drilling operation and thus reduced the torque required when rotating the drill string.

Generally, the presence of xanthan gum increases the viscosity of the drilling fluid at low shear rates, thus it increases the carrying capacity of the drilling fluid which ensures an effective wellbore cleaning. At high shear rates, which occur at the bit, the drilling fluid treated with xanthan gum is low-viscous, thus also ensuring high penetration rates. Shale [19] did highlight that foam or mist may increase lubricity, but the accompanying hole cleaning problems nullify any benefit.

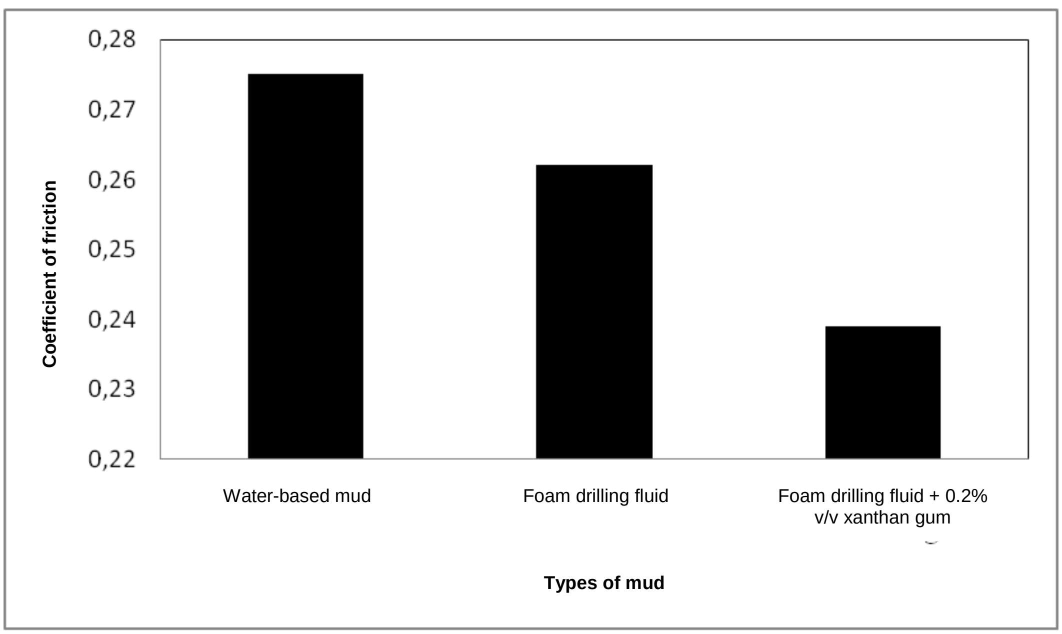


Figure 6 Coefficient of friction for different types of mud

3.6 Plastic Viscosity

Figure 7 shows that the plastic viscosity (PV) recorded for water-based mud, foam drilling fluid, and foam drilling fluid with the addition of 0.2% v/v xanthan gum were 20, 9, and 23 cp respectively. The addition of 0.2% v/v xanthan gum has resulted in increase of bulk viscosity of the said drilling fluid, which is in good agreement with Sarma *et al.* [17]. Generally, foam drilling fluid has a very low solid content, thus it can accommodate better cuttings transport. This positive effect has been compounded by the presence of stabilizer (i.e., xanthan gum) in the foam drilling fluid that has experienced increase in plastic viscosity [20]. The structure of foam – gas bubbles encapsulated by xanthan gum – is found to be more stable, and does not allow the fallback of solids or drilled cuttings which is partly due to the buoyancy and viscous effects, even under no circulation condition. The performance of cuttings transport may be further enhanced via the usage of polymer beads [21].

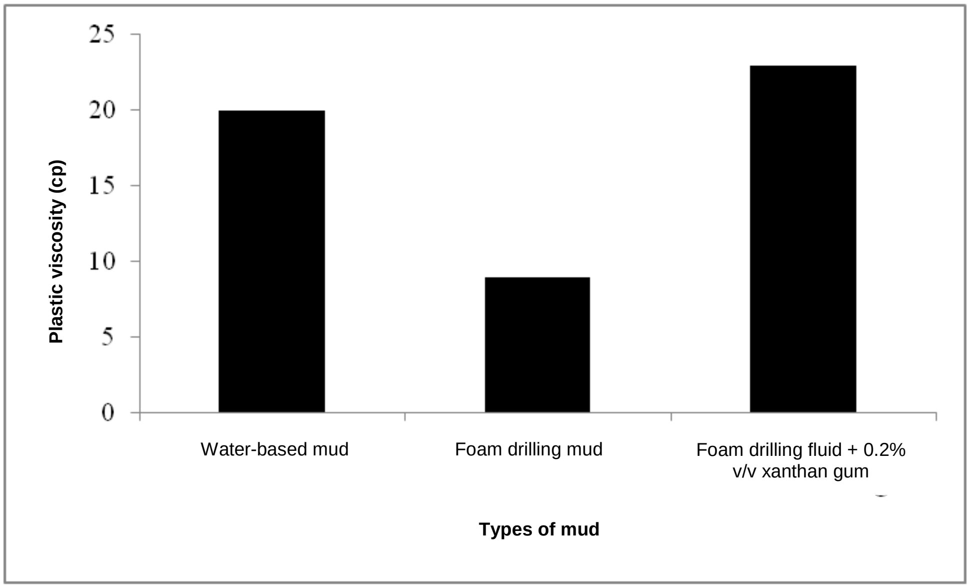


Figure 7 Plastic viscosity for different types of mud

3.7 pH Measurement

The pH test of a mud is to determine the concentration of various ions that affect the ability of reactive clays to produce the desirable mud properties, to formulate and control the chemical composition of the drilling fluids, and also to achieve some degree of compatibility with the formations being drilled. Figure 8 shows the pH measurement for the mud. pH readings for water-based mud, foam drilling fluid, and foam drilling fluid with the addition of 0.2% v/v xanthan gum were 9, 11, and 11 respectively. The alkali characteristic of a surfactant, which normally used in detergent, resulted in high pH reading for foam drilling fluid. Besides, a balance between double-layer repulsive forces influences the stability of the equilibrium thickness of the liquid film, and the liquid film should depend upon the pH of the solutions [5]. The pH was found to be comparable with the pH of commercial foam used in industry, Weatherford KLEAN-FOAM^{TM}, which gave a pH reading in range of 9.5 to 10.5 [22].

Figure 8 pH measurement for different types of mud

4.0 CONCLUSIONS

Based on the experimental results, there were several conclusions could be framed out accordingly:

(1) Anionic surfactant (i.e., sodium dodecyl sulfate) was found to have formed the most stable foam without any additives with half life of 50 minutes.
(2) The presence of xanthan gum in foam drilling fluid with sodium dodecyl sulfate has succeeded in producing a more stable foam drilling fluid with half life of 214 minutes compared to other stabilizers.
(3) The presence of xanthan gum in foam drilling fluid was found to have the capability of reducing friction in drilling operations.
(4) The foam drilling fluid with anionic surfactant and xanthan gum possesses a comparable wellbore cleaning capability.
(5) The pH of the foam drilling fluid with anionic surfactant and xanthan gum was found to be comparable with commercial foam.

Acknowledgements

The authors would like to express their sincere appreciation to Universiti Teknologi Malaysia and the Ministry of Higher Education (MoHE) of Malaysia for the FRGS grant (4F044) given to this research project.

Nomenclature

CMC	- Carboxymethyl cellulose
CTAB	- Cetyltrimethylammonium bromide
ECD	- Equivalent circulation density
HEC	- Hydroxyethyl cellulose
NaCl	- Sodium chloride
PV	- Plastic viscosity
RPM	- Revolutions per minute
SDS	- Sodium dodecyl sulfate
UBD	- Underbalanced drilling
v/v	- By volume
XC	- Xanthan gum

References

[1] Cameron C. 2001. Drilling Fluids Design and Management for Extended Reach Drilling. IADC/SPE 72290 presented at the IADC/SPE Middle East Drilling Technology held in 56 Bahrain. 22–24 October.
[2] Schamp J. H., B. L. Estes, and S. R. Keller. 2006. Torque Reduction Technique in ERD Wells. IADC/SPE 98969 presented at the IADC/SPE Drilling Conference held in Miami, Florida, United Stated of America. 21–23 February.
[3] Aston, M.S., P.J. Hearn, and G. McGhee. 1998. Techniques for Solving Torque and Drag Problems in Today's Drilling Environment. SPE 48939 presented at the 1998 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana. 27–30 September.
[4] Fattah, K.A., S.M. El-Katatney, and A.A. Dahab. 2011. Potential Implementation of Underbalanced Drilling Technique in Egyptian Oil Fields. *Journal of King Saud University- Engineering*. 23: 49–66.
[5] Wikipedia. 2013. http://en.wikipedia.org/wiki/Foam.
[6] Guang C., C. Xingyuan, L. Desheng, C. Xiaonian, C. Liu, and W. Dekun. 2006. The Application of Air and Air/Foam Drilling Technology in Tabnak Gas Field, Southern Iran. IADC/SPE 101560 presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition held in Bangkok, Thailand. 13–15 November.
[7] Liu C., N. Zhang, B. Guo, and A. Ghalambor. 2010. An Investigation of Heavy-Foam Properties for Offshore Drilling. SPE 132464 presented at the SPE Annual Technical Conference and Exhibition held in Florence, Italy. 19–22 September.
[8] Herzhaft B., A. Toure, and S. Saintpere. 2000. Aqueous Foams for Underbalanced Drilling: The Question of Solids. SPE 62898 presented at the 2000 SPE Annual Technical Conference and Exhibition held in Dallas, Texas. 1–4 October.
[9] Hutchins R.D. and M.J. Miller. 2005. A Circulating-Foam Loop for Evaluating Foam at Conditions of Use. SPE 80242 presented at the 2003 SPE International Symposium on Oilfield Chemistry held in Houston. 5–8 February.
[10] Rojas Y., S. Kakadijan, A. Aponte, R. Marquez, and G. Sanchez. 2001. Stability and Rheological Behavior of Aqueous Foams for Underbalanced Drilling. SPE 64999 presented at the 2001 SPE International Symposium on Oilfield Chemistry held in Houston, Texas. 13–16 February.
[11] Schramm, L. 1994. *Foams: Fundamentals and Applications in the Petroleum Industry*. Advances in Chemistry Series 242, American Chemical Society, Washington, D.C.
[12] ExpotechUSA. 1996. *Lubricity Tester Instruction Manual: Model 212 EP*. Houston: ExpotechUSA.
[13] American Petroleum Institute. 2009. *Recommended Practice for Field Testing Water-based Drilling Fluid.* API-RP-13B-1. 4th Edition. Dallas: American Petroleum Institute.
[14] Schelero, N., G. Hedicke, P. Linse, and R.V. Klitzing. 2010. Effect of Counterions and Co-ions on Foam Films Stabilized by Anionic Dodecyl Sulfate. *Journal of Physic Chemical.* 114(47): 15523–15529.
[15] Koehler, S.A., S. Hilgenfeldt, and H.A. Stone. 2000. A Generalized View of Foam Drainage: Experiment and Theory. *Langmuir.* 16: 6327.
[16] Martinez A.C. and A. Maldonado. 2007. Foaming Behaviour of Polymer-surfactant Solutions. *Journal of Physic.*
[17] Sarma, D.S.H.S.R., J. Pandit, and K.C. Khilar. 1988. Enhancement of Stability of Aqueous Foams by Addition of Water-soluble Polymers-measurements and Analysis. *Journal of Colloid and Interface Science.* 124(1): 339–348.
[18] Argillier J-F., S. Saintpere, and B. Herzhaft. 1998. Stability and Flowing Properties of Aqueous Foams for Underbalanced Drilling. SPE 48982 presented at the 1998 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana. 27–30 September.
[19] Shale L.T. 1994. Underbalanced Drilling: Formation Damage Control During High-Angle or Horizontal Drilling. SPE 27351 presented at the SPE International Symposium on Formation Damage Control held in Lafayette, Louisiana. 7–10 February.
[20] Martins A.L., A.M.F. Lourence, and C.H.M. de Sa. 2001. Foam Property Requirements for Proper Hole Cleaning while Drilling Horizontal Wells in Underbalanced Conditions. SPE Drilling and Completion. December. 195-200.
[21] Nur Suriani Mamat, Issham Ismail, Shahrir Hashim, azmi Kamis and Aizal Haziq Abdul Razak. 2013. The Performance of Polymer Beads in Water-based Mud and Its Application in High-temperature Well. *Journal of Petroleum Exploration and Production Technology.* Published with open acess at springerlink.com.
[22] Weatherford International Ltd. 2008. *KLEAN-FOAM® Foamer-Surfactant Drilling-Fluid System*. Houston, Texas: Weatherford.