Design of Inhibitive Water Based High Temperature Tolerable Fluid Systems

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Abstract-.
Demand of the oil and gas energy is increasing very drastically. Conventional hydrocarbon reservoirs contain beneath the sealing cap rock (shale) and easily move towards wellbore are at the depletion stage. Therefore, drilling engineers in collaboration with mud engineers, geologists and geophysicists are looking for innovative materials to drill unconventional hydrocarbons reservoir which are distributed at the basin scale and cannot be approached easily. Most of the geothermal systems and some of the unconventional reservoirs have high pressure high temperature (HPHT) conditions. Conventional micro-macro organic drilling mud additives with heat insulator in nature can minimize efficiency while drilling HPHT wells. Oil-based muds (OBM) are strictly restricted due to high toxic level and poor emulsion stability at HT. However, this proposal aims to suggest formulation of KCl polymer drilling fluids with certain additives that enhance rheological performance under elevated temperatures, yet maintain expected functions including shale inhibition characteristics. Despite an impressive amount of experimental work has been done over drilling additives and their effect over rheological behavior and shale inhibition, this study specifically aims to look into the problem considering elevated temperatures. Thus, main emphasis will be given towards the rheological stability of KCL polymer muds under elevated temperatures by using various additives. This work will hope fully trigger further development and new research topics in the area of drilling muds system.

Keywords- Drilling additives, Nanoparticles, HTHP, Drilling Fluids

I. Statement of the Problem

As conventional oil & gas reserves face depletion, development of unconventional shale plays have brought a solution for the steady increase in high-energy demands during the last decade. See Figure 1 presents the historic production of different type of energy in the United States from 1980 to 2016 and a projection until 2040. The increment trend observed for oil & gas since 2006 was supported in the development of the unconventional reservoirs.

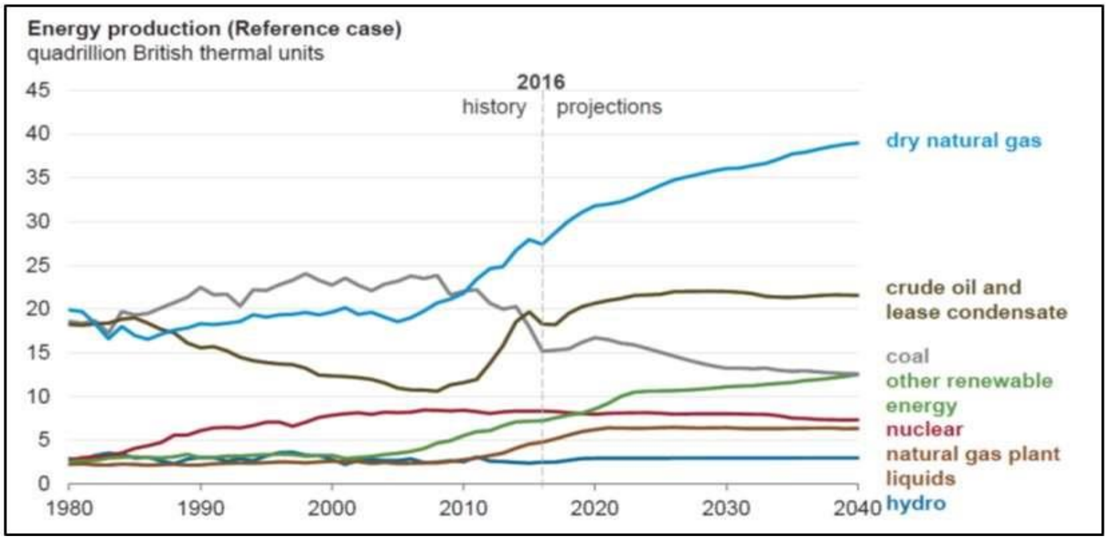

Figure 1- US Energy production history & projection (EIA 2017).

This positive scenario helped the United States to decrease its energy dependence from importations by 25% and set the country in a position close to gas demand self- sufficient [10]. Figure 2 compares the net energy trade in the United States. Since 1980 the country was dealing with a yearly increase in energy importations until 2006 when unconventional shale reservoirs became a decisive player in the United States economy.

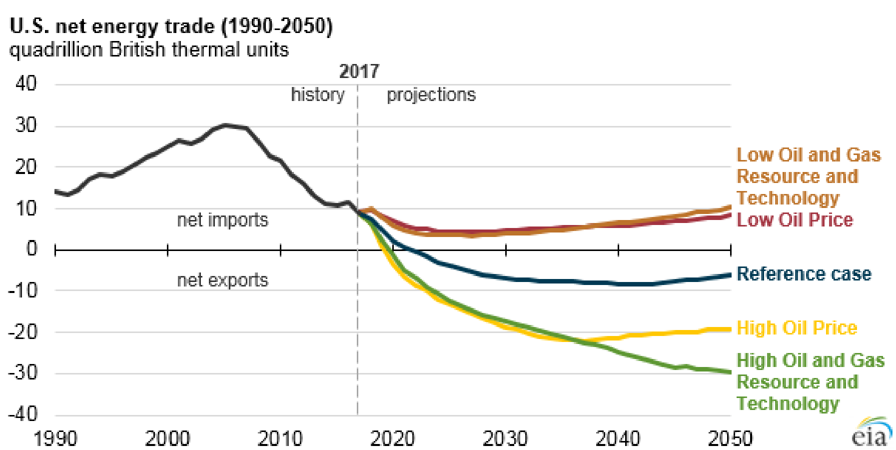

Figure 2- US Net energy trade (EIA 2017).

In the upcoming decades, the United States will continue to support their energy plans on the unconventional shale reservoirs. Many improvements have been done on the two techniques applied to develop the unconventional shales, horizontal drilling, and hydraulic fracturing [11]. However, wellbore stability problems related to shale formations still represent the major problem to overcome during the drilling operations [12] and is thought that the main reason is due to the undesirable interaction between shale formations and water-based drilling fluids [13].

The latter represents a challenge, since 75% of the total drilled length worldwide has been accounted to shale formations [14] and these are responsible for about 90% of wellbore stability problems [42]. Despite these drilling fluid are also responsible to minimize formation damage due to shale hydration and swelling. Although oil-based mud (OBM) can be used to achieve these goals, environmental and economic concerns limit its applications. Thus, researchers started to focus on the design of high-performance water-based muds (WBM) to drill through shale plays [42].

Arising from stringent environmental policies and legislation, the oil and gas industry's effort is geared towards the development of environment friendly fluids that could perform like OBM with respect to its efficiency, toxicity, fluid loss and cost [15]. Consequently, a lot of research have been undertaken towards formulating a high performance WBM's. For any drilling operation the following factor are considered in the selection of drilling fluid; the type of formation to be drilled; the water used in preparing the drilling mud; and the effect on the environment [1]. One of the widely used additives in drilling fluids is polymer. The function of polymer in drilling mud is to provide viscosity, fluid loss control, shale inhibition and prevent dispersion of clay [16]. However, the selection of the right additives that can make water-based muds more stable and effective at higher temperatures remains a big challenge. In addition to this, biopolymers are additives that are used almost in all water based muds; but, when exposed to higher temperatures it becomes a major challenge running them successfully. The low stability of biopolymers thus makes them unreliable for drilling operations under elevated temperatures.

In recent years, researchers have been evaluating the use of Nanoparticles (NP) in different oil & gas applications including drilling fluids [17]. NP can be defined as a particle with a diameter size less than 100 nm. Due to its size, it is believed that NP can plug the shale nanopores reducing the factors that lead to the wellbore instability [18]

In order to evaluate the potential of NP in WBM for shale plays, shale-fluid interaction, and nanoparticles stability need to be studied in detail. The best approach is to follow a methodology that characterizes the shale rock, then select the appropriate NP and evaluate it under different environmental conditions and finally observed the overall drilling fluid performance by means of rheology, filtration, inhibition and most importantly stability at elevated temperatures. This research aims to emphasize the rheological stability of KCL polymer muds under elevated temperatures using various additive.

OBJECTIVE

1) To design an experimental study for formulating high performance water base mud system using different additives
2) This study specifically will aim towards using the right amount of KCl concentration in addition with other additive to maintain the rheological stability of KCl polymer WBM under elevated temperature
3) As KCl polymer fluid is used in almost all WBM and not only unconventional formation, shale fluid interaction will be studied at a general level. In other words, this proposal aims to suggest formulation of KCl polymer drilling fluids with certain additives that enhance rheological performance under elevated temperatures, yet maintain expected functions including shale inhibition characteristics at a general level
4) Use of nanoparticles, nanocomposite and other additive will be investigated and the best additive will be selected to design a WBM mud system which will hopefully bridge this gap in the industry and open doors to new research topics in drilling mud system

II. Scope and Methodology

This research aims to design a high performance KCL polymer water based mud that not only enhances the rheological stability but also shale inhibition. A general outline can be described as KCL polymer fluids will be formalized using various additives, such as relevant nanoparticles, to increase the temperature resistance of mud. Rheological characterization test will be conducted using Fann 75 viscometer for elevated temperatures up to 350°F and lastly to mimic the shale fluid interaction in the well bore annulus tests will be conducted using The University of Tulsa Drilling Research Projects (TUDRP) Shale Fluid Interaction Facility at elevated temperatures. The research is not only limited to nanoparticles but other additives as well that enhance the temperature resistance of KCl polymer based muds.

Figure 3 - Shale Fluid Interaction facility of TUDRP

III. Literature survey

1. Classification of drilling muds

Selection of drilling muds mainly depends on geology, petrophysical data, previous field drilling data and availability for disposing of the drilling muds after no longer in use. Classification of drilling muds based on their fluid phase alkalinity, dispersion, and the type of additives used in their formulation. Drilling muds are divided into different classes (Figure 4).

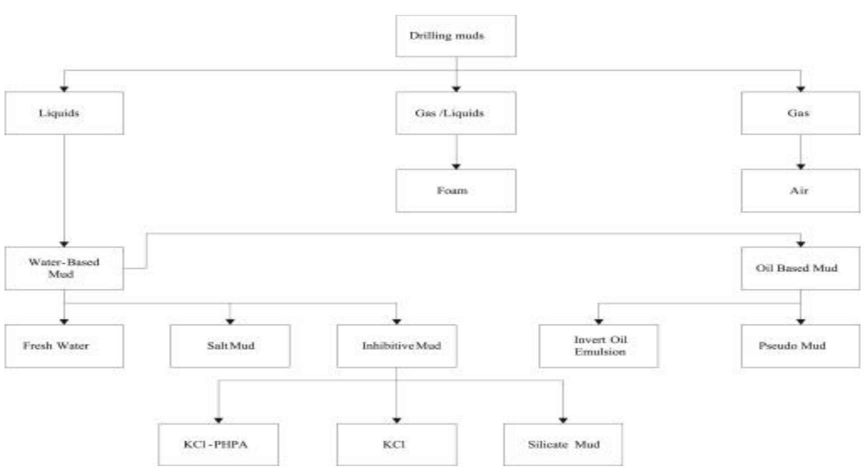

Figure 4- Classification of drilling mud

Water-based mud WBM is an inexpensive, environmentally friendly and most extensively used drilling mud [2]. WBM comprises of spud muds, bentonite muds, phosphate muds, organic thinned muds such as red muds, lignosulfonate muds, lignite muds, and organic colloid muds [4]. World's 80% oil and gas wells are drilled by using WBM [2]. Recently, Maliardi et al. [5] planned high performance WBM which may diminish ecological effects and improve operational execution. Additionally, it was demonstrated that rheological properties in particular viscosity, density and coefficient of friction (CoF) were improved with less environmental issues. Elkatatny et al.[6] suggested that WBM has consistent rheological properties. In contrast, Ahmed et al. [8] showed that the WBM has poor filtration properties, and shale inhibition features compared to OBM. Nonetheless, WBM is a cost effective drilling mud, and if formulated well it provides good rheological properties [7]. In order to develop performance of WBM equivalent to OBM some compounds are added in WBM (see Table 1).

Table 1- Water-Base mud components

Compound	Function	References
Glycol based	Shale inhibitor	[9]
Flowzan	Viscosity enhancer	[19]
Caustic soda	pH control	
Carboxymethyl cellulose	Filtrate reducer	[20]
Acrylamide copolymer, polypropylene glycol (PPG)	WBM Shale inhibitor	[21]
Polyacrylamide		[22]
Alkali silicates		[23]

2. Inhibitive WBM

Inhibitive WBM described as a mud that prevents hydration of clays. Inhibitive WBM is sea water muds, lime muds, gypsum muds, and saturated salt water muds. WBM without inhibitors increases the problems of shale contamination and swelling which can have undesirable effect over drilling operation and increases well drilling cost [24]. The main purpose of inhibitive WBM is to protect shale stability often identified by wellbore collapse [25]. Normally, chlorides and sulphates salts are added in WBM to prepare inhibitive WBM. These salts can reduce the water ionic activity of drilling muds than shale water to lower down diffusion of ions and water molecules in the shale [2]. Potassium muds are the most extensively accepted inhibitive WBM system for drilling water responsive shale. Potassium ions attach to clay surfaces and provide stability to the shale when exposed to drilling muds. Potassium ions hold the cuttings together, preventing cutting dispersion into finer particles. KCl is most extensively used inhibitor in oil and gas drilling operations. KCl improved the rheological and shale inhibition characteristics [41]. Potassium carbonate, potassium acetate, potassium hydroxide, potassium lignite, and PHPA have potential for improvement of shale inhibition and rheological characteristics [48]. In contrast, recently Sehly et al. [25] investigated that high concentration of KCl in drilling muds could destabilize rheological properties and formed two phase separation in the mud. Additionally, drilling cuttings contaminated with KCl become highly toxic and cannot be disposed at environmentally sensitive areas [25]. Therefore, small quantity of KCl in conjunction with polymer is used to minimize environmental and operational hurdles. For rheological control different types of polymers are used such as xanthan gum [46], PHPA [26], CMC [47], and PAC [2] . However, PHPA is commonly used for shale encapsulation [26]. Survey of various studies used Inhibitive WBM is summarized in Table 2.

Table 2- Review of findings using inhibitive WBM using KCl

Material	Problem	Finding	References

Addition of high molecular weight PHPA, and KCl (shale inhibitor) in inhibitive WBM were reported.	Effects of the polymer and KCl-WBM were studied over prevention of shale swelling and improvement of rheological properties.	Results revealed that high molecular weight PHPA could control shale swelling and rheological problems at HPHT conditions without use of KCl. In addition, lubricity was also increased with use of PHPA polymer. Potassium ion was highly flocculated that could adversely affect the rheological properties in particular filtrate volume. Therefore, KCl load play very critical role in preparation of drilling muds	[26]
Inhibitive WBM and OBM mud were reported.	Accretion problems have been observed by using high load KCl mud. Thus accretion slowed down drilling such as blocked drill lines and accumulated solids inside transportation system	Inhibitive WBM improved by using of tetra potassium pyro phosphate (TKKP) in the place of KCl and KCl-polymer to reduce accretion. TKKP mud reduced shale swelling down to 2.0%. Nonetheless, accretion was still reported by using test TKKP	[27]
Fresh water, NaCl, fluid loss agent, xanthan gum, shale inhibitor, dispersion suppressant, and accretion suppressant.	Use of enhanced inhibitive WBM in place of SBM in ultra-deep wells. Test fluid must met both operational and environmental criteria	Inhibitive WBM improved the rheological properties in ultra-deep water well and fulfilled both operational and environmental criteria	[40]
Soda ash, bentonite, xanthan gum, par R (fluid loss and viscosifier), par L (fluid loss and viscosifier), barite and KCl (shale inhibitor) were used for preparation of inhibitive WBM.	Effects of KCl on physical properties of the mud.	Adverse effect on physical properties in particular viscosity was found due to contamination of shale with basic WBM. Later, rheology was improved with the addition of KCl inhibitor	[41]
KCl (shale inhibitor) and CMC were used to prepare inhibitive mud. Nonethless complete compositions of drilling muds were not reported.	To examine effect of KCl concentration on viscosity, chemical stability, and aging	Findings indicated that yield point increased with the aging time at 0.1 M of KCl. In addition, KCl at higher concentration such as 0.2 M formed suspension between two phases. Therefore, mud became unstable. The	[25]

		behaviour of inhibitive WBM.	suspension formed a supernatant and sedimentation phase. Beside that high KCl concentration drilling mud can be toxic to disposal area and drilling environment

3. Additives for Viscosity Control

Commercial clays are used to control the viscosity of drilling muds. One ton of commercial clay can provide 15 cp of viscosity [45]. Native clays usually result high solid content compared to bentonite to provide the same density. The viscosity of clay is affected by the salts either by formation water or salt added for a particular purpose. Due to hydration, the dispersion of clay is influenced by the magnesium (Mg+) ions and calcium (Ca+) ions. Viscosity cannot be increased so high. It can minimize the flow efficiency of drilling mud such as poor transportation drill cuttings, required high pump power, and more chances of differential pipe sticking. Survey of various studies used different types of viscosity additives is given in Table 3.

Table 3 Review of findings of additives for viscosity control

Mud type	Additive	Concentration	Rheological Property	Reference
HPHT-WBM	Bentonite	Unknown	Viscosity	[37]
HPHT-WBM	Xanthum - gum	7 lb		[38]
	Clay	10lb		[39]
	Xanthum-gum and PAC	1lb, 2lb		[49]
Inhibitive WBM	Xanthum gum	14lb, 1.5 lb		[40]
Nanoparticle Based Drilling muds	Bentonite	Unknown	NA	
Nano Based Drilling muds	PAC			[50]

4. Additives for Density Control

Barium sulphate commonly termed as a barite used in drilling muds as a weighting agent. Beside that other weighting agents are hematite, and high density marbles. Drilling muds can attain 9–19 ppg density by mixing barite with the water [43]. Density can also be controlled by calcium carbonate. However, the technical challenge faced by the drilling engineers is to vary density of drilling muds function of pressure. Ravi et al. [44] suggested elastic particles can be used to formulate variable density drilling muds. Density of drilling muds varied as a function of pressure in subterranean formation. The elastic particles are usually polymer of styrene, vinylidene chloride, a copolymer of styrene, divinylbenzene, acrylonitrile, and a copolymer of styrene and acrylonitrile [44]. Typical range of density and concentration of weighting agent for drilling muds are given in Table 4.

Table 4- Review of Density ranges and concentration of Barite [34]

Type of Mud	Weighing Agent	Concentration of weighing agent	Rheological Property	Density Range
Inhibitive WBM	Barite	68 lb/bbl	Density	10.5 – 13
High Performance WBM		91 lb/bbl		10
HPHT WBM		492 lb/bbl		17.5 at 176°C

5. Filtration control additives and Shale Inhibitors

One of the major attributes of filtration control additives is to produce a thin impermeable cake to prevent fluid loss. It is very important to consider this factor especially when drilling through permeable formations. Shale instability arises as a result of adsorption of water by shale and therefore this cannot be neglected. Review of Filtrate control additive and Shale inhibitors are provided in Table 5

Table 5- Review of Filtrate Reducer and Shale Inhibitors

Filtrate Reducer	Reference	Shale Inhibitors	Reference
Encapsulated lime	[28]	Modified poly amino acid	[31]
Encapsulated oil absorbent polymers	[29]	Polyacrylamide	**Error! Reference source not found.**
Divinylsulfone, cross linked Poly(galactomannan) gum	[30]	Cellulosic material Starches Betaine Partially hydrolyzed polyacrylamide	[33]

6. Effect of Temperature on Drilling Fluids

One of the most challenging problems for drilling fluids is the temperature operational range of the chemicals use to mixed it. The temperature at the bottom of the hole increases as the well deepens, and it is important that the drilling fluid maintains acceptable rheological and filtration properties. These properties of the mud are strongly related to the temperature effects and under downhole conditions may be very different from the ones measured at the surface leading to misinterpretations that can generate future undesirable wellbore conditions (e.g. wellbore instability, tripping difficulties). When drilling fluids are exposed to high temperatures, the portion of the fluid that is at the lower part of the wellbore becomes excessively thick, a situation that becomes worse under static conditions in which the prolonged heating may cause the drilling fluid to experiences a solidification process [35].

The effect of temperature on drilling mud can be attributed to the complicated interplay of several causes, some of which are more dominant than others. Factors such as reduction in the degree of hydration of the polymers, reduction of the viscosity of the suspending medium, increased dispersion of clay particles, and an increase in the degradation rate of additives. Since all these processes take place in the drilling fluid simultaneously as the temperature is varied, an interpretation of the observed results will only be possible in cases whereby some of the effects are predominant and as such be easily identified.

One immediate effect of high temperatures is the detrimental effect on drilling fluid rheology, which can increase cuttings settling and affect the hydraulic capabilities as well as experiencing some degree of flocculation in the drilling mud. The latter will lead to a poor quality-filter cake, thick enough to increase the risk of differential stuck pipe due to the larger contact area between the drill string and the filter cake.

On the other hand, the poor permeability condition of the filter-cake will increase the filtrate into the formation. Thermal degradation of filtrate control-additives and viscosifiers aggravate the problem previously described. As an example, at temperatures below 300 °F, starches in the drilling fluid start to experience hydrolysis and depolymerization of thinners or irreversible chemical reactions can take place leading to a complete degradation of the drilling mud [36].

Finally, the temperature should be treated as one important contaminant in drilling fluids. Its detrimental effect on polymer hydration, clay flocculation, and rheological problems as described previously are a few points that support this claim. The most interesting part of all of this is that temperature has no treatment. The initial design of the drilling fluid with the appropriate chemicals is the only preventive solution to the problem.

7. Potential additive for drilling fluids that enhances the temperature resistance

7.1. Nanomaterials in drilling mud

Nanomaterial has enhanced the performance of drilling muds because of their distinctive type such as highly enhanced physiochemical, electrical, thermal, and hydrodynamic properties [53]. Multifunctional nanoparticles applications attract a variety of industries such as bio medical technology, electronic, coating industry and material composite [54]. Similarly, successive efforts are also taken by the petroleum institutions to develop advanced material for nano sensing or nano robots to collect the underground reservoir valuable data for the investigation of reservoir performance and deliverability [55]. Material added in drilling muds at the dimension between 1 and100 nm are called nanomaterial [53] [55]. Nanomaterials compared to their bulk phase materials offer potential for many applications of oil and gas industry [53]. Various applications of nanomaterials in drilling muds have been reported in the literature in particular controlling the mud filtrate volume [52], minimizing differential pipe sticking [56], drilling and production at HPHT conditions [57], enhancing shale stability[55]. Nano fluids can be described as mixtures of solid nanomaterials suspended in base fluids. Generically, nanomaterials are metal oxides which support heat transfer by increasing thermal conductivity [138]. Shape orientation and structure of nanoparticles greatly influenced the properties of nano fluids. Nanomaterial provided ease to formulate better drilling muds due to their better dispersion, minimum particle logging and adjusting physical properties such as heat transfer, wettability and surface tension [60] [61]. Nano fluids are offering promising thermal conductivities features compared to conventional fluid such as fresh water [141]. 5% vol of copper oxide nanomaterial could improve 22.4% heat transfer efficiency of the solution. Improved thermal conductivities of nanomaterial fluids attracted investigators to use nanomaterial in HPHT drilling muds [57]. Srivatsa and Ziaja [52]. examined the effect of nanomaterial on physical properties of nano fluids. Viscosity, gel strength, pH and filtrate loss volume were measured with and without nanomaterial. It was found that nano material fluids improved rheological properties of the drilling muds. Sadeghalvad and Sabbaghi[3].presented an experimental study on synthesis of TiO_2-polyacrylamidenanocomposite and used in drilling mud. It was observed that the additive improved the viscosity, filtration loss volume at ambient pressure and temperature, and deposited a thin impermeable mud cake. WBM contains bentonite and other conventional additives can improve rheological properties of drilling muds. These additives have radical effect over viscosity of drilling muds due to presence of polymers such as acrylamide, acrylic acid guar gum [64], and xanthan gum [63]. These polymers do not sustain HPHT downhole environment and may raise difficulties during drilling under extreme HPHT down-hole environment [62]. When metal oxides nanoparticles are compared with polymers; the nanoparticles have better heat transfer characteristics. Review of studies reported the use of nanoparticles in drilling muds is shown in Table 6.

Table 6- Review of Nanoparticle under HPHT

Drilling Mud	Nano Particle	Optimization	Reference
WBM	CuO and ZnO	Controlled Viscosity and prevented fluid loss at HPHT	[51] [52]
	nanosilica	Prevention of water into shale, reduced loss of viscosity and prevented differential sticking at HPHT	[58] [56]
	Montmorillonite and polygorskite nanoparticles	Levelled out viscosity, gel strength, fluid loss, spurt loss and density at HPHT	[59]

7.2 Other promising additive

Table 7- Promising Additive

Mud	Promising additive with KCl	function
WBM	Barite	Weighing agent/ Density control
	Xanthum gum and PAC	Viscosity control
	CuO and ZnO nanoparticle	Controlled Viscosity and prevented fluid loss at HPHT
	nanosilica	Prevention of water into shale, reduced loss of viscosity and prevented differential sticking at HPHT

IV. Proposed Experimental Work

At least three different additives will be tested to increase the temperature resistance, promising ones based on literature review are listed as follows; nanoparticles such as i) Zno, ii) CuO and iii) nanosilica. Xanthum gum and/or PAC will be used for viscosity control with barite as weighing agent, KCl inhibitor will be used a primary additive to improve rheological stability but test will be conducted to ensure the right concentration of KCl under elevated temperatures.

At least three different concentrations will be used to formulate mud samples and rheological categorization test will be conducted at least at 5 temperature values including room temperature and one extreme high temperature that is greater than 300°F. Rheological categorization will be investigated via Fann 75 viscometer for elevated temperatures and most promising additives and concentrations will be identified. Once most promising additives are identified then these fluid formulations will be tested regarding their shale-fluid interaction performance at a general level.

Note: The additives listed above seems to be the most promising ones, however they are subjected to change once tests are conducted and their performances are revealed. As KCl polymer are used in almost all drilling fluids, KCl will remain to be the primary inhibitor.

V. DELIVERABLES

- Formulation suggestions for KCl polymer inhibitive mud systems resistant to elevated temperatures
- Experimental data for various additives, and comparative information based on their temperature resistance performance
- Final report

VI. INDUSTRY APPLICATION / PRACTICAL USE

Information regarding different additives enhancing temperature resistance of KCL polymer inhibitive muds, which can be used as guidelines during formulating such drilling fluids

VII. ACKNOWLEDGMENTS

I would like to thank University of Tulsa McDougall School of petroleum engineering department and in particular Dr. Evren Ozbayoglu for giving me an opportunity to work on this proposal.

VIII. TIMELINE

Year	2020	2021		2022
Semesters	Fall	Spring	Fall	Spring
Literature review				
Additive identification				
Experimental work				
Data analysis				
Final report				

IX. REFERENCES

[1] Mitchell, Rober, and Stefan Miska. *Fundamentals of drilling engineering*. Society of Petroleum Engineers, 2011
[2] Van Oort E, Bland R, Howard S, Wiersma R, Roberson L. Improving HPHT stability of water based drilling fluids. SPE/IADC drilling conference: Society of Petroleum Engineers; 1997
[3] Sadeghalvaad M, Sabbaghi S. The Effect of the TiO2 /Polyacrylamide Nanocomposite on Water-Based Drilling Fluid Properties. Powder Technol 2015;272:113–9
[4] Lyons WC. Standard Hand Book of Petroleum & Natural Gas Engineering. US: Gulf: Professional Publishing; 1996.
[5] Maliardi A, Sergiacomo M, Del Gaudio L. Successful Application of Innovative Technology Improves Lubricity of High Performance Water-Based Mud Systems in Challenging Environments. International Petroleum Technology Conference. Kuala Lumpur, Malaysia: International Petroleum Technology Conference. p. 1–8; 2014.
[6] Elkatatny SM, Nasr-El-Din HA, Al-Bagoury M. Properties of Ilmenite WaterBased Drilling Fluids for HPHT Applications. International Petroleum Technology Conference. Beijing, China: International Petroleum Technology Conference. p. 1– 15; 2013
[7] Huadi F, Aldea C, MacKereth BM, Mukhlis T. Successful KCl free Highly Inhibitve and Cost Effective WBM Applications, Offshore East Kalimantan, Indonesia. IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition. Ho Chi Minh City, Vietnam: Society of Petroleum Engineers. p. 1–7; 2010.
[8] Ahmed Kamel AH. A Novel Mud Formulation for Drilling Operations in the Permafrost. SPE Western Regional & AAPG Pacific Section Meeting 2013 Joint Technical Conference. Monterey, California, USA: Society of Petroleum Engineers. p. 1–10; 2013

[9] Lee LJ, Patel AD, Stamatakis E. Glycol Based Drilling Fluid. US Patent 6291405 B1; 2001

[10] Charlez, Philippe A., and Pierre Delfiner. "Resilience of the US shale production to the collapse of Oil & Gas prices." *Unconventional Resources Technology Conference, San Antonio, Texas, 1-3 August 2016*. Society of Exploration Geophysicists, American Association of Petroleum Geologists, Society of Petroleum Engineers, 2016

[11] Arthur, James Daniel, Brian K. Bohm, and David Cornue. "Environmental considerations of modern shale gas development." *SPE annual technical conference and exhibition*. Society of Petroleum Engineers, 2009.

[12] Gazaniol, Didier, et al. "Wellbore failure mechanisms in shales: prediction and prevention." *Journal of petroleum technology* 47.07 (1995): 589-595.

[13] Hoelscher, Katherine Price, et al. "Application of nanotechnology in drilling fluids." *SPE international oilfield nanotechnology conference and exhibition*. Society of Petroleum Engineers, 2012.

[14] Lal, Manohar. "Shale stability: drilling fluid interaction and shale strength." *SPE Asia Pacific Oil and Gas Conference and Exhibition*. Society of Petroleum Engineers, 1999.

[15] Apaleke, Adeleye Sanmi, Abdulaziz A. Al-Majed, and Mohammed Enamul Hossain. "State of the art and future trend of drilling fluid: an experimental study." *SPE Latin America and Caribbean petroleum engineering conference*. Society of Petroleum Engineers, 2012

[16] Galindo, Kay A., et al. "High temperature, high performance water-based drilling fluid for extreme high temperature wells." *SPE International Symposium on Oilfield Chemistry*. Society of Petroleum Engineers, 2015.

[17] El-Diasty, A. I., and A. M. S. Ragab. "Applications of Nanotechnology in the Oil & Gas Industry: Latest Trends Worldwide & Future Challenges in Egypt, North Africa Technical Conference and Exhibition." *Society of Petroleum Engineers: Cairo, Egypt* (2013).

[18] Boul, P. J., et al. "185950-PA Functionalized Nanosilicas as Shale Inhibitors in Water-Based Drilling Fluids.(January), 2–5." (2016).

[19] Zolkifile NB. Study of Nanomaterial and Glass Beads on Rheological Properties and Lubricity of Water Based Mud. Malaysia: Universiti Teknologi Malaysia; 2013.

[20] Melbouci M, Sau AC Water-Based Drilling Fluids Comprising Carboxymethylated Raw Cotton Linters. CA Patent 2574498 C; 2011.

[21] Patel BB, Muller TG Compositions comprising an acrylamide-containing polymer and process therewith. US Patent 5684075 A; 1997

[22] Ewanek J. Water-based polymer drilling fluid and method of use. WO Patent 2007041841 A1; 2014

[23] Mullen GA, Gabrysch A. Synergistic mineral blends for control of filtration and rheology in silicate drilling fluids. US; 2001.

[24] Chesser, B. G. "Design considerations for an inhibitive, stable water-based mud system." *SPE Drilling Engineering* 2.04 (1987): 331-336.

[25] Sehly K, Chiew H-L, Li H, Song A, Leong Y-K, Huang W. Stability and Ageing Behaviour and the Formulation of Potassium-Based Drilling Muds. Appl Clay Sci 2015;104:309–17.

[26] Chesser BG. Design Considerations for an Inhibitive, Stable Water-Based Mud System. SPE Drill Eng 1987;02:1–6.

[27] Reid PI, Minton RC, Twynam A. Field evaluation of a novel inhibitive water-based drilling fluid for tertiary shales. European petroleum conference. Cannes, France: Society of Petroleum Engineers. p. 1–10; 1992

[28] Walker CO. Encapsulated lime as a lost circulation additive for aqueous drilling fluids. US Patent 4614599A; 1989

[29] Delhommer HJ, Walker CO. Encapsulated oil absorbent polymers as lost circulation additives for oil based drilling fluids. US Patent 4704213A; 1987

[30] Kohn RS. Thixotropic aqueous solutions containing a divinylsulfone-crosslinked polygalactomannan gum. US Patent 4752339A; 1988

[31] Bruton JR, McLaurine HC. Modified poly-amino acid hydration suppressant proves successful in controlling reactive shales. SPE annual technical conference and exhibition. Houston, Texas: Society of Petroleum Engineers. p. 1–9; 1993.

[32] Schlemmer R, Patel A, Friedheim J, Young S, Bloys B. Progression of water[HYPHEN]based fluids based on amine chemistry– can the road lead to true oil mud replacements. In: Proceedings of the 2003 AADE National Technology Conference, Practical Solutions for Drilling Challenges April 2003, p 1–3.

[33] Alonso-Debolt M, Jarrett MA. Drilling fluid additive for water-sensitive shales and clays, and method of drilling using the same. EP Patent 668 339; 1995.

[34] Dreveton E, Lecourtier J, Ballerini D, Choplin L. Process using gellan as a filtrate reducer for water-based drilling fluids. US Patent 5744428A; 1998

[35] Ali, M. Shahjahan, and M. Ali Al-Marhoun. "The effect of high temp., high pressure and aging on water-base drilling fluids." (1990).

[36] Chesser, Bill G., and Dorothy P. Enright. "High-temperature stabilization of drilling fluids with a low-molecular-weight copolymer." *Journal of Petroleum Technology* 32.06 (1980): 950-956.

[37] Gomez SL, He W. Fighting wellbore instability: customizing drilling fluids based on laboratory studies of shale-fluid interactions. IADC/SPE Asia Pacific drilling technology conference and exhibition. Tianjin, China: Society of Petroleum Engineers. p. 1–10; 2012.

[38] Falope FD, Orodu OD, Osayande I, Uhunoma U. Improved drilling efficiency via enhanced water based mud in the Niger Delta. SPE Nigeria annual international conference and exhibition. Lagos, Nigeria: Society of Petroleum Engineers. p. 1– 11; 2014

[39] Deville JP, Fritz B, Jarrett M. Development of Water-Based Drilling Fluids Customized for Shale Reservoirs. SPE International Symposium on Oilfield Chemistry. The Woodlands, Texas, USA: Society of Petroleum Engineers. p. 1–10; 2011.

[40] Watson P, Meize B, Aldea C, Blackwell B. Eastern Gulf of Mexico: inhibitive waterbased drilling fluid sets ultra-deepwater records. IADC/SPE Drilling Conference. Dallas, Texas: Society of Petroleum Engineers. p. 1–14; 2004

[41] Joel O, Durueke U, Nwokoye C. Effect of KCL on rheological properties of shale contaminated water-based mud (WBM). Glob J Inc(USA) 2012:12.

[42] Mody, Fersheed K., and A. H. Hale. "Borehole-stability model to couple the mechanics and chemistry of drilling-fluid/shale interactions." *Journal of Petroleum Technology* 45.11 (1993): 1-093.

[43] Water-Based Mud PS. Additives, ⟨http://petroleumsupport.com/about/⟩, [accessed 06.09.15]; 2015

[44] Ravi KM, Whitfill DL, Reddy BR, Szymanski M. Variable density fluids and methods of use in subterranean formations. US Patent 7749942 B2; 2010.

[45] Finis T Beneficiated clay composition for use in drilling fluids. US Patent 3220946A; 1965.

[46] Fritz B, Jarrett M. Potassium Silicate Treated Water-based Fluid: An Effective Barrier to Instability in the Fayetteville Shale. IADC/SPE Drilling Conference and Exhibition San Diego, California: Society of Petroleum Engineers. p. 1–6; 2012.

[47] Iscan A, Kok M. Effects of polymers and CMC concentration on rheological and fluid loss parameters of water-based drilling fluids. Energy Sources, Part A 2007;29:939–49.

[48] Fink JK. Petroleum engineer's guide to oil field chemicals and fluids. Boston: Gulf: Professional Publishing; 2012.

[49] Ewy RT, Morton EK. Wellbore Stability Performance of Water Base Mud Additives. SPE Annual Technical Conference and Exhibition. Denver, Colorado, USA: Society of Petroleum Engineers. p. 1–9; 2008

[50] Kang Y, She J, Zhang H, You L, Song M. Strengthening shale wellbore with silica nanoparticles drilling fluid. Petroleum; 2016.

[51] William, Jay Karen Maria, et al. "Effect of CuO and ZnO nanofluids in xanthan gum on thermal, electrical and high pressure rheology of water-based drilling fluids." *Journal of Petroleum Science and Engineering* 117 (2014): 15-27.

[52] Srivatsa, Jayanth T., and Malgorzata B. Ziaja. "An experimental investigation on use of nanoparticles as fluid loss additives in a surfactant–polymer based drilling fluid." *IPTC 2012: International Petroleum Technology Conference*. European Association of Geoscientists & Engineers, 2012.

[53] Amanullah, Md, Mohammed K. AlArfaj, and Ziad Abdullrahman Al-abdullatif. "Preliminary test results of nano-based drilling fluids for oil and gas field application." *SPE/IADC drilling conference and exhibition*. Society of Petroleum Engineers, 2011.

[54] Saidur, Rahman, K. Y. Leong, and Hussein A. Mohammed. "A review on applications and challenges of nanofluids." *Renewable and sustainable energy reviews* 15.3 (2011): 1646-1668.

[55] Hoelscher, Katherine Price, et al. "Application of nanotechnology in drilling fluids." *SPE international oilfield nanotechnology conference and exhibition*. Society of Petroleum Engineers, 2012.

[56] Javeri, Saket Mahesh, Zishaan Muhamad Wajid Haindade, and Chaitanya Bhalchandra Jere. "Mitigating loss circulation and differential sticking problems using silicon nanoparticles." *SPE/IADC Middle East Drilling Technology Conference and Exhibition*. Society of Petroleum Engineers, 2011.

[57] Nguyen, Phuong-Tung, et al. "Evaluation on the EOR potential capacity of the synthesized composite silica-core/polymer-shell nanoparticles blended with surfactant systems for the HPHT offshore reservoir conditions." *SPE International Oilfield Nanotechnology Conference and Exhibition*. Society of Petroleum Engineers, 2012.

[58] Cai, Jihua, et al. "Decreasing water invasion into Atoka shale using nonmodified silica nanoparticles." *SPE Drilling & Completion* 27.01 (2012): 103-112.

[59] Abdo, J., and M. D. Haneef. "Clay nanoparticles modified drilling fluids for drilling of deep hydrocarbon wells." *Applied Clay Science* 86 (2013): 76-82.

[60] Serrano, Elena, Guillermo Rus, and Javier Garcia-Martinez. "Nanotechnology for sustainable energy." *Renewable and Sustainable Energy Reviews* 13.9 (2009): 2373-2384.

[61] Ravisankar, R., et al. "A review on oxide and metallic form of nanoparticle in heat transfer." *International Journal of Engineering Science and Technology* 6.3 (2014): 63.

[62] Fakoya, M. F., and S. N. Shah. "Enhancement of filtration properties in surfactant-based and polymeric fluids by nanoparticles." *SPE Eastern Regional Meeting*. Society of Petroleum Engineers, 2014.

[63] Garcıa-Ochoa, F., et al. "Xanthan gum: production, recovery, and properties." *Biotechnology advances* 18.7 (2000): 549-579.

[64] Dairanieh, I. S., and S. M. Lahalih. "Novel polymeric drilling mud viscosifiers." *European polymer journal* 24.9 (1988): 831-835.