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Evaluation of Design Criteria for Gravel Pack and Hydraulic Fracturing Fluids

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ABSTRACT: *Viscous gravel-carrier and highly viscoelastic crosslinked fluids used in gravel packing and hydraulic fracturing respectively often contain polymers which are capable of damaging the formation. Thus after placement, the polymers must be degraded by gel breakers and be removed from the wellbore or formation to prevent formation damage, facilitate good regained conductivity and permeability of the proppant pack, which is essential for good well hydrocarbon production. The action of the gel breaker must be controlled; it must not act too fast to break the gel, causing premature deposits of the proppant in the tubings before getting to the desired zone, creating early screen out, thereby jeopardizing the job. The gravel carrier-fluids must break at the right time for successful deposit of the proppant in the targeted zone and facilitate good fluid recovery and adequate wellbore clean out. The polymer degradation process by gel breakers is a function of many factors, therefore making it difficult to predict the break time of gravel packing and hydraulic fracturing fluids. Consequently, so much time is usually spent to conduct laboratory experiment, combine with the rigours of search through archives for similar tests for preliminary engineering simulations or for fluids design proposal. This paper therefore details a review of design criteria for gravel packing and hydraulic fracturing fluids with a view of proffering solution to production enhancement fluid design challenges presently encountered in the laboratory and field operations.*

Keywords: *Crosslinked gel, Formation Damage, Gravel Pack, Hydraulic Fracturing, Proppant.*

I. INTRODUCTION

Optimal and economic production of petroleum from the reservoir is the goal for a successful well. Soft and unconsolidated formations with compressive strength lower than 1000psi, with low natural cementatious materials, usually produce sand or fines as the reservoir fluid is being produced [1]. Sand production is undesirable and has no known economic value. Sand production can cause various problems. According to Abass *et al.* [2], some known sequences of sand production include the following:

- Reduced well production
- Sand bridging in tubings, casings, screens, perforations, pipes and separators
- Damage of surface and subsurface equipment and gadgets
- Casing or formation collapse
- High cost of well maintenance
- Environmental problem associated with sand handling and disposal

More so, Abbas *et al.* [2] stated the techniques available to control or minimize sand production from hydrocarbon wells as follows:

- Periodic well maintenance/workover
- Production rate reduction
- Selective completion / production from intervals with good compressive strength
- Sand consolidation with resinous materials
- Resin coated gravels
- Stand-Alone Screen or Liners
- Gravel packing

Selecting a particular sand control technique depends on the type of well completion and the formation’s geo-mechanical properties. Gravel packing is the often preferred and very reliable sand control technique [3]. Gravel packing involves packing the annulus between a steel screen placed in the wellbore in the open or cased hole with gravels of specific size, meant to check the passage of the produced formation sand or fines, without causing any adverse effect on the well's productivity [2]. Gravel packing can be done for both Open-hole and Cased-hole completions. Gravel placement technique is much simple in vertical wells and much more difficult and complex in highly deviated or horizontal wells [4]. Shunt Packing which involves placing perforated shunts or pipe in the annulus, attached to the screen to provide alternate paths for gel slurry flow, is a more reliable method of ensuring complete pack of the annulus by eliminating sand bridging in highly deviated or horizontal wells [5]. A visco-elastic fluid with high gravel suspension capability is recommended for the Shunt packing technique [6].

A carrier fluid is required to transport gravel from the surface to the target zone in the wellbore or formation. If the carrier fluid does not provide adequate sand suspension quality, sand may be deposited before getting to the desired interval and premature sand screen out could occur. A variety of fluid systems have been used as gravel carrier fluids and this includes different types of brines, diesel, crude oil, foam, viscous linear gels and crosslinked gels [1]. Packing with brine, which is popularly referred to as water pack, does not permit transport of high proppant concentration but relies on the fluids velocity from the high pump rates to transport gravel. It usually forms tight annular proppant pack but could have high leak off rate in permeable zones, which could result to sand bridging and poor packing [7]. However, water pack does not contain polymer, which has the potential to cause formation and this has made water to be popular.

Viscous packs, also known as Slurry packs, uses viscous fluids for gravel transport. This decreases the tendency of inter-mixing of formation sand and proppant, a problem identified with water pack; it allows transports of high proppant concentration; the potential of non-uniform packing and formation damage from polymer residue is one of its short comings [7][8[9].Gel breakers are usually added to viscous gravel carrier fluids to reduce the viscosity downhole and the gel break time depends on temperature, type and concentration of breakers, type and concentration of the polymer, fluids pH and the shear rate [10].

The objective of well stimulation or production enhancement is to increase the production of hydrocarbon from the reservoir. The commonly used techniques for stimulation of oil wells include: hydraulic fracturing, fracpack, matrix acidizing (carbonate and sandstone) and fracture acidizing [11]. Acidizing can be used to remove the near wellbore formation damage, dissolving part of the formation to facilitate the flow of hydrocarbon to the wellbore. In this, the fluid pumping pressure may be below the fracture gradient of the formation as in matrix acidizing or may be high enough to fracture the formation as in the case of fracture acidizing [12].

Hydraulic fracturing can be used to produce hydrocarbon from tight formations with low permeability. This involves pumping of specially formulated fluid system into the formation at rate and high pressure sufficient to crack open the formation, thereby creating highly conductive paths for hydrocarbon to flow to the wellbore and the created fractures usually extend beyond the damaged zone. The created fractures may further be etched with an acid or propped open with the aid of gravels after the pressure has been released [11]. Hydraulic fracturing, though commonly used for stimulating low permeability wells and to bypass damage in moderate permeability formation, can also be used in high permeability formation (k>10md) to optimize production and control formation fines [8][13].

The viscous nature of fracturing fluid is a very important property necessary for creation of good fracture geometry and improves the sand transport quality of the fluid; more viscous fluids tend to generate wider and higher fractures, give better sand suspension property and are usually more thermally stable [14]. Once the fractures have been created and proppant deposited in the factures, the viscous fracturing fluid and the filter cakes must be cleaned out to enable production of hydrocarbon with little or no impairment and help to attain a high regain conductivity of the proppant bed [15].

Gel breakers, which are usually added to the gel at surface during the mixing stage, are used to reduce the viscosity of the polymers by breaking them into smaller fragments of lower molecular mass. It's very important to control the action of the gel breakers; it must not work too fast to cause premature breaking of the gel, thereby reducing its sand carrying capability, but must acts quickly enough to reduce the viscosity of the gel, allow deposit of the proppant and permit good flow back of the fluid [16]. The breaker reaction depends on temperature, concentration of breaker, polymer concentration and pH [17].

Extensive research has led to the development of various gravel pack and fracturing fluid systems with the right property to march the various challenging environment of different wellbores. Selection of the appropriate additives to formulate and engineer the right fluid system is often based on laboratory testing and optimization of the fluid designs.The commercial success of a well to a great extent depends on the fluid design. There are many variable affecting the fluids design, therefore making it difficult to predict the fluids behavior. Consequently so much time is spent in optimizing gravel pack and fracturing fluids in the laboratory.

Therefore, this paper present a review of the advancement in the use of water-based polymer fluids for gravel pack and hydraulic fracturing operations and the challenges involve in the fluids design and optimization.

II. REVIEW OF COMMONLY USED POLYMERS FOR GRAVEL PACK AND HYDRAULIC FRACTURING

Polymers are utilized in almost all wellbore operations, including gravel packing and hydraulic fracturing. These polymers include the following: hydroxyethyl cellulose (HEC), carboxymethyl hydroxyethyl cellulose (CMHEC), guar, hydroxypropyl guar (HPG), carboxymethyl hydroxypropyl guar (CMHPG), starch, xanthan, welan gum, scleroglucan, diutan and carrageenan [18]. The helical polymers (scleroglucan, xanthan, welan gum and diutan) are thermally stable, while those of random-coil type (guar, HPG and HEC) undergo severe loss of viscosity at high temperatures [18]. The most commonly used polymers for gravel packs are HEC, HPG, methyl cellulose and xanthan; most of these polymers contain varying amount of residue that can damage the gravel bed permeability [8].

The fluids used in gravel packing serve three major functions: transportation of gravel to the desired interval, facilitate gravel to pack compactly and allow fluid to be produced back after the gravel pack has been placed without affecting the production capacity or permeability of the gravel pack bed and formation [8].McGowen *et al.* [8] also noted that various fluid systems have been used in hydraulic fracturing operations and this includes the following:

- Conventional linear gels: Guar, HPG, CMHPG, HEC and CMHEC
- Borate crosslinked fluids
- Organometallic crosslinked fluids
- Aluminum crosslinked phosphate ester oil gels.

Guar and its derivatives (HPG and CMHPG) are the most common polymers or viscosifiers used in formulating hydraulic fracturing fluids because of their abundance, relative low cost, flexibility in design optimization, low friction pressure and high proppant carrying capability [19]. These fluids suspend and transport prop pants, create fractures, length/width and provides fluid-loss and leak off control during the hydraulic fracturing process [17]. The required high fluid viscosity is generated by crosslinking the polymer molecules with a crosslinker such as borate B(III), titanate Ti(IV), or zirconate Zr(IV) ions; the crosslinked fluid provides more viscosity at a much lower polymer concentration than adding more polymer, which would result to high pumping or treating pressure and sand wetting [14][17]. The insoluble residues contain in these polymers are obtained from the manufacturing process and some are created during the breaking of the fluid, and this could cause damage to the conductivity of the proppant pack [19].

Borate crosslinked fluids are the most widely used in fracturing operations; Guar gum and its derivative are crosslinked with monoborate ions B(OH)4-, whose source could be boric acid, borax, or organoborate salts [19].Monoborate ion can also be formed from hydrolysis of boric acid; the monoborate ion forms complexes with the cis-hydroxyl groups present in the guar gum or HPG at pH values greater than 8.5 [20]. Example of hydrolysis of sodium tetraborate is shown in equations (1) and (2).

$$Na_2B_4O_7 + 10H_2O \rightarrow 2Na^+ + 2B(OH)_3 + 2B(OH)_4^- + 3H_2O \qquad (1)$$

$$B(OH)_3 + OH^- \leftrightarrow B(OH)_4^- + H_3O^+ \qquad (2)$$

In borate crosslinking, there are fast exchange equilibria of monoborate ion on the cis-diols of the guar (galactomannam) polymer, with the borate ions forming 1:1 complexes with the pairs of cis-diol and a few of 2:1 complexes that yield the crosslinking [21]. Combination of polymer with adequate crosslink sites with the proper number of crosslinking ions, necessary to build a structural network, is required for the formation a good borate crosslinked gel [21].

Proper pH control is very essential during mixing and preparation of gravel pack and fracturing fluids. Fluid pH affects initial polymer hydration rate, crosslinking properties, viscosity stability, gel break properties and bacterial control [14].

III. REVIEW OF POLYMER DEGRADATION AND GRAVEL SUSPENSION PROPERTIES EXPERIMENT

Gel breakers are used to reduce the viscosity of polymer fluids, both for linear gravel pack and crosslinked fracturing gels, to facilitate good clean out of the wellbore [14][22]. Gel breakers act by breaking the long polymer molecules into smaller sizes of lower molecular weight [20]. The three available breakers for water based polymeric fluid systems are acids, enzymes and oxidizers [23][24].

Almond [25] studied the effect of breaker concentration, breaker type, crosslinker and pH of guar / cellulose based fracturing fluids and demonstrated that the residual polymer after break can cause reduction in flow by plugging the formation.

Powell *et al.* [26] observed that optimal fluid performance with biopolymer viscosifiers such as xanthan and welan, depends on reaching a minimum critical polymer concentration (CPC). The CPC is affected by the type of fluid and welbore conditions such as, temperature, salinity, average shear rate, shear history, velocity gradients, hole angle, polymer configuration, polymer size, density and concentration of suspended solids. More so, the suspension and transport propeties of xantan and welan, correlate directly to low-shear-rate-viscosity (LSRV) and elasticity (G'), which cannot be measured with conventional field viscometer. More so, xanthan and whelan polymers were observed to show excellent static suspension and dynamic transport of suspended solids, as compared to other viscosifiers; therefore they are prefarably used in highly deviated and horizontal drilling and workover operations.

Jones *et a1.* [5] reported a new alternate path gravel packing method, designed to eliminate formation of annular sand bridges, usually associated with conventional gravel pack technique, especially in highly deviated or horizontal well. The results from laboaratory experiment performed using a 30-ft full scale gravel pack simulator indicate 95 to 100% gravel pack efficiencies as compared to 65 to 80% obtained with conventional gravel packing procedures, based on visual observations. This technique was also reported to be more flexible and permit wider ranges in slurry rheology and pumping rates. The experiment was conducted for 36lbs/1000 gal XC polymer gel, using Baker sand control gravel pack simulator which as the capability of varying inclination angle between 0 and 90°.

Al-Mohammed *et al.*[20] studied the degradation of high pH borate crosslinked gels, guar and HPG, with various concentrations sodium bromate and chlorous acid breakers, using Brookfield viscometer, model PVS, to measure the fluid's apparent viscosity. Test results, as shown in Figs 1 to 5, showed that the degradation time of gel was a function of breaker type, breaker concentration and the polymer loading. The results also showed that the rate of degradation of fluids prepared using HPG was faster than those prepared using guar gum; guar-based fluids produced more residue than fluids prepared using HPG; surface tension of gel filtrate decreases with temperature and is independent of oxidizer type.

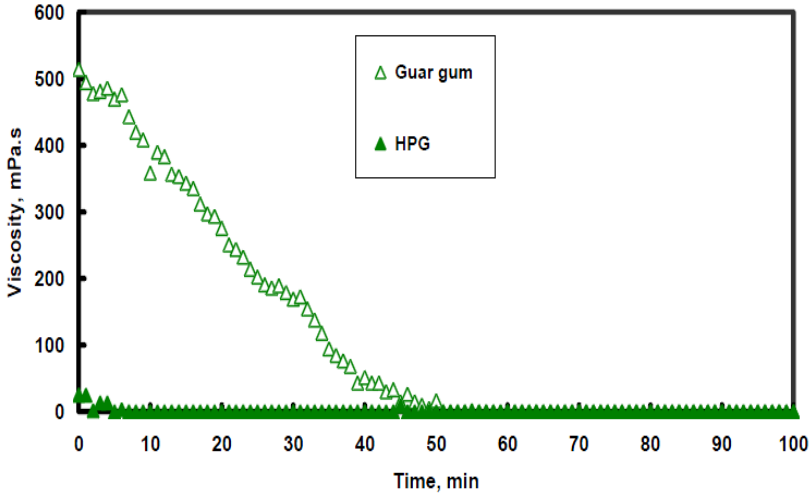

Figure 1: Viscosity of HPG and guar gums (35ppt) with 0.5 vol % sodium bromate at 130 °C, shear rate of 17s^{-1} and a pressure of 300psi [20].

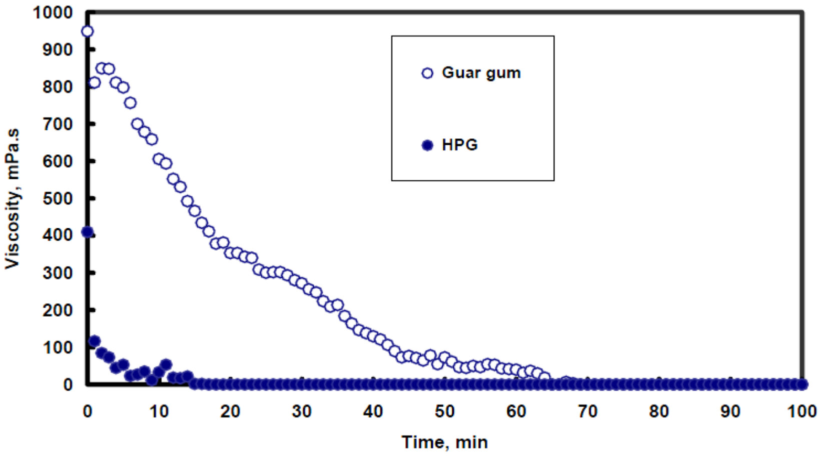

Figure 2: Viscosity of HPG and guar gums (40ppt) with 0.5 vol % sodium bromate at 130 °C, shear rate of 17s^{-1} and a pressure of 300psi [20]

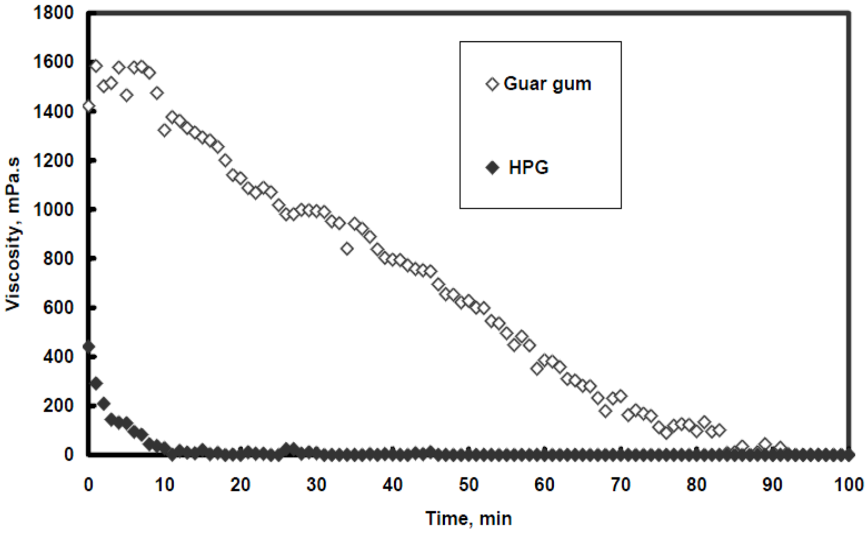

Figure 3: Viscosity of HPG and guar gums (45ppt) with 0.5 vol % sodium bromate at 130 °C, shear rate of $17s^{-1}$ and a pressure of 300psi [20].

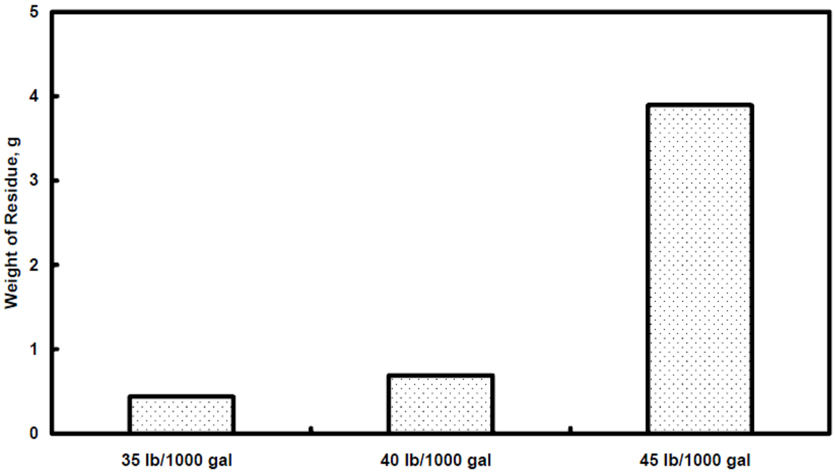

Figure 4: Weight of residue produced after heating different polymers loading of HPG with 0.5% vol. sodium bromate in see-through cell at 140 °C and 300psi after 4 hours [20].

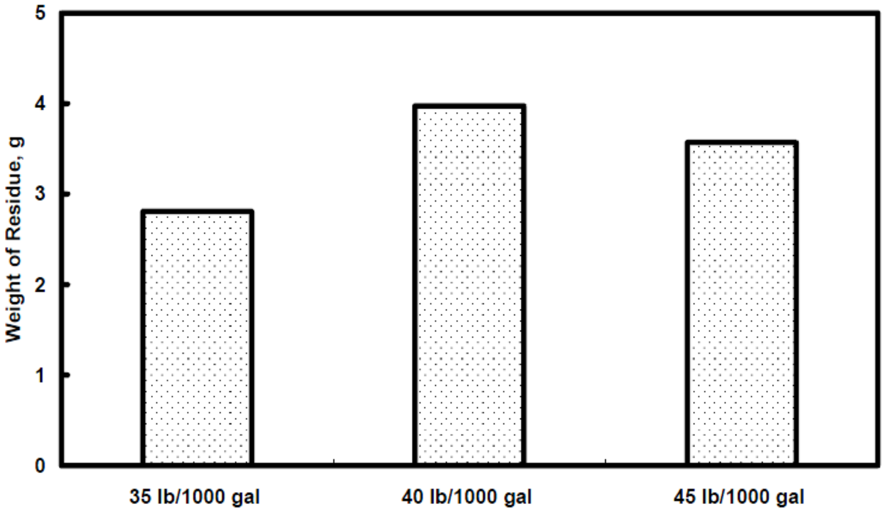

Figure 5: Weight of residue produced after heating different polymers loading of guar gums with 0.5% vol. sodium bromate in see-through cell at 140 °C and 300psi after 4 hours [20].

Harris et al. [27], worked on the prediction of proppant transport from rheological data, noting that the most of fracturing treatments use viscoelastic fluids to ensure good proppant transport; different viscous fluids have varying degrees of elasticity and this includes linear polymer gels, crosslinked polymer gels, foams, emulsions and surfactants gels. In a test performed at a shear rate of 100 $s^{-1}$for biopolymer fracturing fluid,using HPHT viscometer with concentric cylinder, the viscosity decreases with time for different concentrations of breakers as shown in Fig. 6.

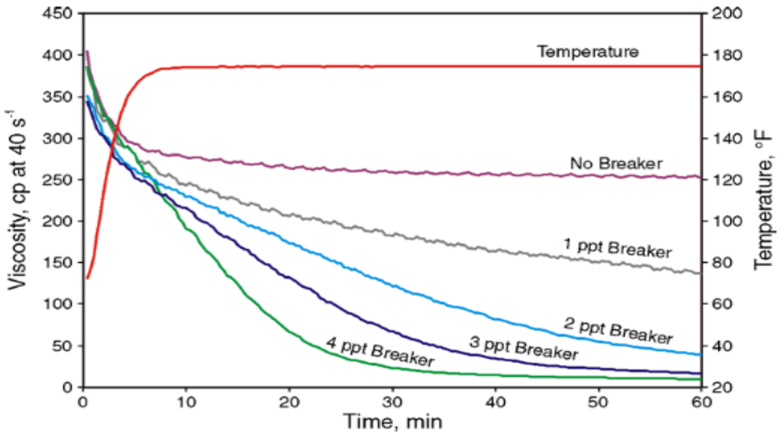

Figure 6: Viscosity of biopolymer with different concentration of breakers [27].

Harris and Sabhapondit [28] analyzed the components of hydraulic fracturing fluids and how they can be effectively combined to formulate aqueous gelled fluid that have adequate rheological properties to generate good fracture geometry and good transport properties. It was noted that Guar crosslinked at high pH, while CMHPG crosslinked at low and high pH as depicted in Fig 7.

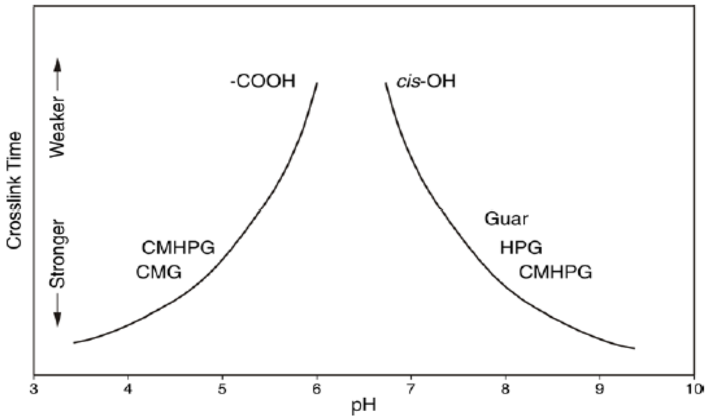

Figure 7: Crosslinking rate of metal complex ion with guar and guar derivatives [28].

Joel *et al.* [29] derived a model equation for break time of gravel pack fluids at different breaker concentrations and temperatures. The model equation,as described in equations (3), (4) and (5), can help predict gel break time of a particular gravel pack fluid at different concentrations of gel breaker and at various temperatures. The equation was derived for a particular type of gelling agent and for a particular breaker. The test results showed that gel break time is a function of breaker concentration and temperature.More so the results of the model agreed with the experimental data in a margin of less than 10% deviation as shown in Figs. 8, 9 and 10.

$$(\mathrm{BRT}) = ae^{-bC_B} \quad (3)$$

$$a = -3097.9 \ln(T) + 17188 \quad (4)$$

$$b = 0.00756\, e^{0.0129T} \quad (5)$$

Where BRT is Break Time in minutes; C_B is Breaker concentration in gal/1000gal; T is temperature in ^{o}F; a and b are coefficients that depends on temperature.

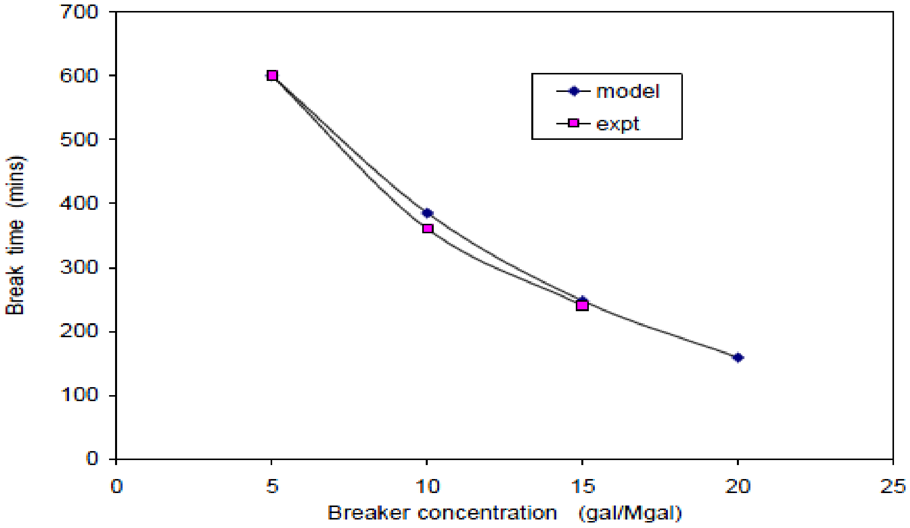

Figure 8: Comparison of experimental and model break time @ 190 °F [29]

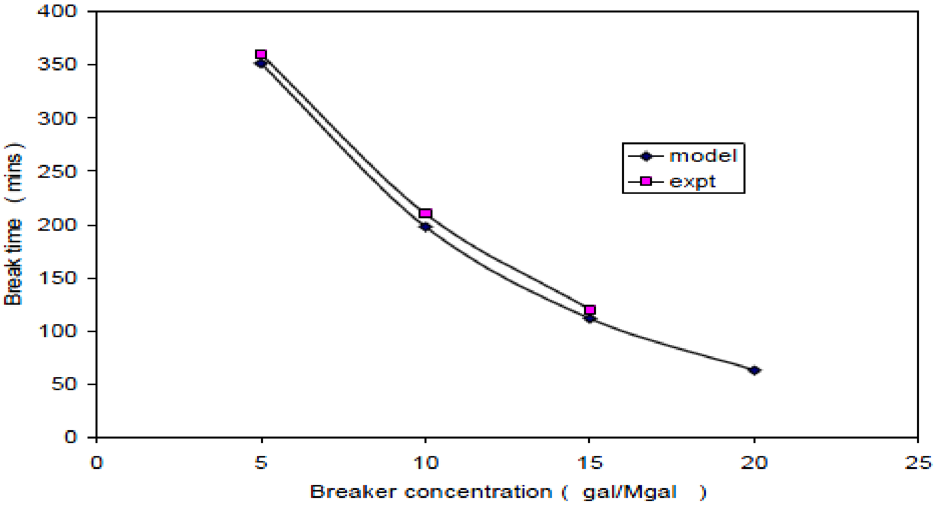

Figure 9: Comparison of experimental and model break time @ 210 °F [29]

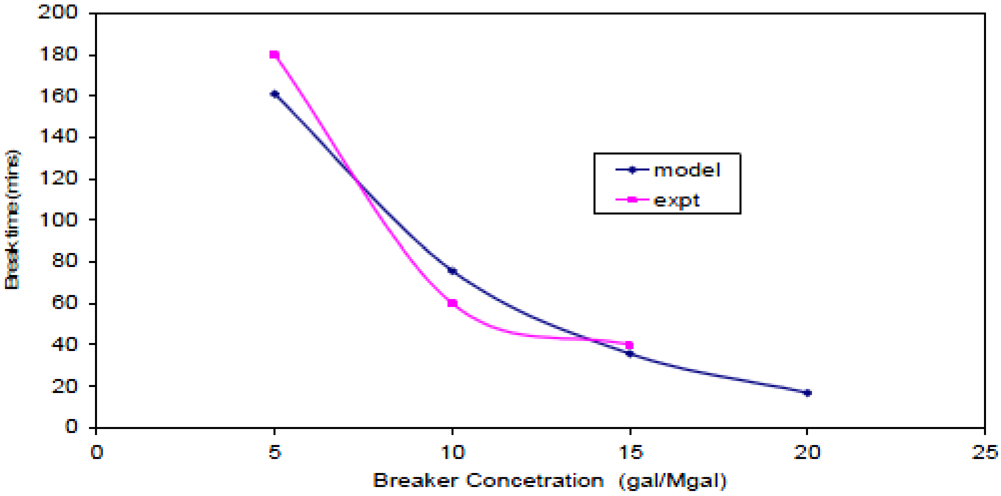

Figure 10: Comparison of experimental and model break time @ 230 °F [29]

Sarwar *et al.* [22] investigated the effectiveness of oxidizer breakers, such as sodium persulfate, ammonium persulfate, sodium peroxide, calcium peroxide and galactomannanase enzyme in temperature range from 75 to 300 ^{o}F. The breakers generated varying amount of residue between 5 to 7% wt., with enzyme leaving the least residue, though source of the residue was not investigated. Persulfates breakers were observed to be too reactive at temperatures above 140^{o}F (60 ^{o}C), this signifies high probability of premature polymer degradation occurrence that could lead to early proppants screenout for high temperatures application. The remedy to this is the utilization of encapsulated delayed breakers [17].

Patil *et al.* [16] worked on the development of encapsulated breakers, such as oxidizers and chelants, which allowed for a controlled release of the breaker. The studies was carried out using Zr-crosslinked CMHPG and borate crosslinked HPG fluids in dynamic rheology tests. The results show that the polymer blend matrix, used in encapsulating the breaker, releases the breaker slowly and breaks the fracturing fluid in a corolled manner. Test results is shown in Fig. 11.

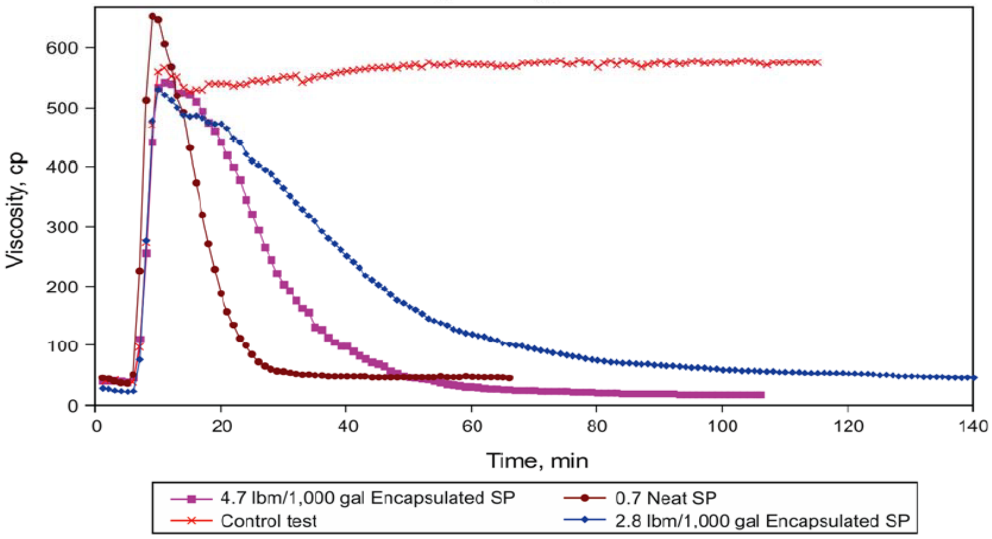

Figure 11: Viscosity profile for 30lbm/Mgal CMHPG, 0.5 GAL/Mgal Zr crosslinker at 200 ^{o}F [16].

Montgomery [24] studied the effect of breaker concentration on the retained permeability and the result is shown in Figure 12. The retained permeability increases with increase in breaker concentration.

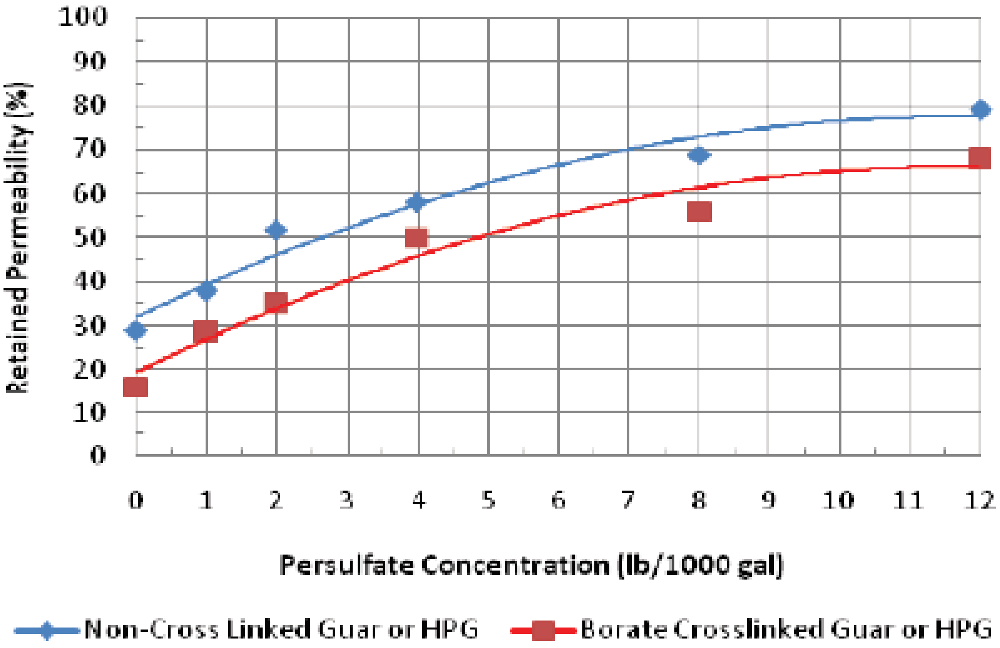

Figure 12: Effect of breaker concentration on retained permeability [24].

Al-Muntasheri [17] did a critical review of hydraulic fracturing fluids in the last decade and captured the advances in the design of water based fracturing fluids. He noted that guar-based and cellulose based polymers are the most commonly used in preparing fracturing fluids. Guar-based polymers, containing a minimum of 5% wt. residue, was used for fracturing treatments of wells at temperatures less than 300 °F, to generate high viscosity fracturing fluids and to minimize leak off. In order to minimize formation damage associated with the use of this type of polymers, lower concentrations of polymers were employed with crosslinkers, capable of generating high viscosity. More so, Guar has thermal stability issues at temperatures above 180 °F. Therefore derivatized guar such as hydroxypropyl guar (HPG) and carboxymethyl hydroxypropyl guar (CMHPG) were introduced and showed better performance than guar. Synthetic polymers such as 2-methy acrylamide-2-methylpropanesulfonic acid (AMPS) and copolymers of partially hydrolyzed polyacrylamide (PHPA)-AMPS-vinyl phosphonate (PAV), produced sufficiently high viscosity at temperature up to 450 °F. In order to minimize formation damage associated with polymers-based gels, viscoelastic surfactants (VES) were used, but was observed to have thermal stability issues at temperatures above 240 °F (115 °C), except when used in high concentration. VES does not also provide adequate leakoff [30].

IV. CONCLUSION

Gravel Pack and Hydraulic Fracturing fluids properties such as hydration rate, viscosity, rheology, gravel suspension capability, thermal stability and polymer degradation depends on my variables such as salinity, pH, temperature, shear rate, shear history, polymer type, gel loading and type/concentration of gel breakers.

The selection of the right gelling agent, gel breaker and other additives is key and very vital when formulating fluids for hydraulic fracturing and gravel pack sand control treatments.Chemical breaker systems have been developed through extensive research to provide a clean and accurate breakdown of the viscosifying polymers after the hydraulic fracturing treatment or the gravel pack is in place, to improve regained conductivity and ensure good permeability of the proppant pack.

Breaker type and concentration are selected based on the bottom hole temperature application and takes into account the slurry transit time. The break time of polymers depends on temperature, type and concentration of breakers, type and concentration of polymers and pH of the fluid.

However it is difficult to accurately predict the break time of gravel pack and fracturing fluids at different temperatures for different gelling agents because of the many variables.Consequently, a lot of time is often spent in performing laboratory tests before appropriate concentrations of additives, especially breaker, is obtained and fluid design optimized.

There is need to develop a model that can predict break time of polymers used for production enhancement operations in order to reduce the time spent in searching through archives to obtain a preliminary fluid design for engineering simulation or initial project proposal. This will also serve as quality check and minimize the risk of having Non-Productive Time and associated Cost of Poor Quality.

More so, some visco-elastic fluid systems with excellent gravel suspension properties, like xanthan and diutan, suitable for gravel packing highly deviated or horizontal wells, are difficult to break, especially at low temperatures. Further studies are needed to obtain shorter break time of the polymers at low temperatures.

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