

Rheological properties of fracturing fluids

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ABSTRACT

Fracturing fluids play an important role in hydraulic fracturing treatments. The rheology of hydraulic fracturing fluids affects transport, suspension, and deposition of proppants, as well as flow back after placement. They should also be capable of developing the necessary fracture width to accept proppants or to allow deep acid penetration. Compatibility with formation fluids and material must also be taken into account.

The rheology of fracturing fluids is fundamental for hydraulic fracturing design, i.e. prediction of fracture growth and geometry. Accurate measurements and good understanding of their rheological properties are essential for designing and executing an optimum treatment. Failure in selection of fracturing fluid will result in unsuccessful treatment in terms of reservoir conditions, oil production, and net present value.

Borate cross-linked fluids have been widely used as a fracturing fluid in the oil industry. Experimental studies have been conducted to investigate the rheological properties of two borate cross-linked fluids. In this article the linear viscoelastic properties of these fracturing fluids are described in detail.

INTRODUCTION

Reservoir stimulation is one of the main activities during petroleum production from

an oil well. The main purpose is to enhance the production and thus, to increase the ultimate economic recovery. The treatments are intended to remedy, or even improve, the natural connection of the wellbore with the reservoir¹. There are two main areas of interest for a stimulation treatment and that is the wellbore zone included its proximity and the rest of a reservoir

Stimulation is needed to remove damages (skin zones) around the wellbore. Different kinds of stimulation technology are generally used depending on the area of interest. These can be acid washing, matrix acidizing, acid fracturing or hydraulic fracturing. The latter technique will be addressed in this paper.

Formation damage and consequently the formation of a skin effect can be caused by a lot of different failures either during drilling, completion or during production. And so skin analysis has to be performed prior to stimulation treatment.

Hydraulic fracturing

Hydraulic fracturing is stimulation treatment by creating fractures to connect the wellbore with the undamaged reservoir. It is a well-stimulation technique that is most suitable to wells in low and moderate permeability reservoirs ($k < 10$ mD), that do not provide commercial production rates even though formation damages may have been removed by acidizing treatments. A

low leak-off fracturing fluid is essential to reduce the injection rate requirement. Thus the rheological properties must be able to hinder flow of the liquid phase into the formation.

A hydraulic fracturing job consists of three stages: i) A fracturing fluid is injected into the formation at a rate high enough, given the rheological properties of the fluid, to overcome the compressive earth stresses and the rock's tensile stresses. At this pressure the rock fails then allowing a fracture to be formed. ii) Continued fluid injection increases the fracture's length and width. iii) Proppant injected into the fracture prevents the fracture to close when the pressure is reduced and make sure the fracture remains open as a high permeable zone when the well is placed on production. These proppants could be small particles of either sand or ceramics².

To be able to fracture the formation without too high a pump rate, the fracturing fluid has strong gel like characteristics. These viscoelastic properties will also keep the proppant in suspension during placement. The fluid viscosity and elasticity should decrease after the completion of the fracturing treatment to allow the placement of the proppant and a rapid fluid return through the fracture. Controlling the time at which the viscosity break occurs is very important to avoid proppant flow back.

Most fracturing fluids used are water-based. This is due to both economical and technical advantages compared to oil-based fluids. Within water-based fracturing fluids one divides between three types which also reflects the historical development of fracturing fluids. The first type is called linear fracturing fluids where polymers are added in order to increase viscosity and to increase its ability to transport proppants. The second type is called cross-linked fracturing fluids and here cross-linkers came into use. This has now partly been replaced by a third type called delayed cross-link systems.

Others have studied the rheological behavior of cross-linked fluids with respect to pressure^{2,3}. In these studies an increasing pressure was found to reduce the cross-linking effect. However, in the present paper pressure effects are not studied. Rheological properties of two cross-linked fluids are studied with respect to temperature.

EXPERIMENTAL CONDITIONS

Sample preparations

The fracturing fluids used for our measurements were borate cross-linked fluids (hydroxypropyl guar polymer hydrated in brine and cross-linked with borate cross-linker) delivered by Halliburton with the following properties:

Fracturing Fluid 1: tailored for 50°C application (3.6 kg of polymer per m³ of fluid, with surfactant, KCl brine, and pH buffer to a pH of 9.5).

Fracturing Fluid 2: tailored for 100°C application (4.8 kg of polymer per m³ of fluid, with surfactant, KCl brine, and pH buffer to a pH of 11).

Rheological measurements

For our rheological measurements a Physica UDS 200 rheometer was used equipped with a concentric cylinder configuration named Z3 DIN. Here the inner cylinder has a diameter of 25 mm while the measuring cup has a diameter of 27.11 mm.

RESULTS AND DISCUSSION

Amplitude sweep

For the amplitude sweeps used to locate the Linear Viscoelastic (LVE) range of our fracturing fluids we used a constant angular frequency, ω , of 10s⁻¹. In Fig. 1 is shown the results of the amplitude sweep on a type 2 fracturing fluid measured at a temperature of 20°C. In this figure the amplitude strain, γ , is plotted on the x-axis while the storage modulus, G' , and the loss modulus, G'' , are

plotted on the y-axis, both axes in a logarithmic scale. At the lowest amplitudes the curves indicate a region of unstable measurements. This is expected to be due to limitations of the rheometer in combination with the configuration used for our measurements. Thus, to establish the upper limit of the LVE range we used the measured values of G' and G'' within the range from $\gamma = 0.03$ to 0.3 to establish LVE plateau values. The upper limit was said to be at the point where either the G' or the G'' values were found to deviate with more than $\pm 5\%$ from their respective plateau values. Thus, the upper limit of the LVE range for the measurements shown in Fig. 1 was found at an amplitude strain of $\gamma = 0.575$.

As the upper limit of the LVE range was found to increase with temperature for both our fluids and that the limits of the LVE range for Fluid 1 was found to be higher than that of Fluid 2 at all temperatures, a strain value of $\gamma = 0.1$ was chosen as the strain value used for all our frequency sweeps. This strain rate being well inside the LVE range of our fluids and as it was found during our angular frequency sweeps, that when using this strain value the lowest stable readings with respect to angular frequency were obtained using our measuring configuration.

It is noticeable from Fig. 1 that both curves are increasing from their linear region value before decreasing. According to Mezger⁴ this indicates that an increasing proportion of the deformation energy (loss modulus, G'') is being used up to change the structure before the final breakdown takes place. It can also be noted from Fig. 1 that in the LVE region the elastic behavior dominates over the viscous behavior, $G' > G''$. In accordance with Mezger⁴ this implies that our fluid can be said to have a gel character and therefore a certain form stability. Fluid 2 was found to have a gel character at all our measured temperatures. Fluid 1 was also found to show a gel character up to the design temperature of 50°C . Above this

temperature for amplitude sweeps at a temperature of 60 and 70°C it was found that $G'' > G'$ which indicate a fluid with a liquid character.

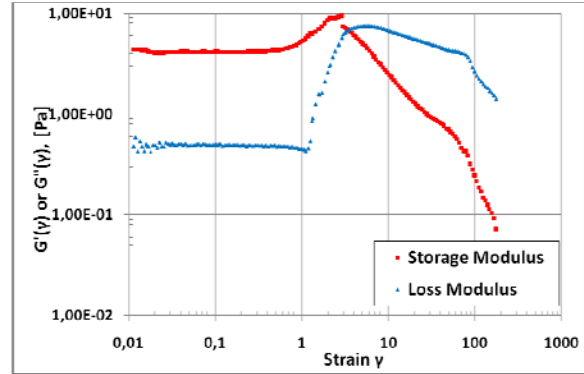


Figure 1. Typical G' (Storage Modulus) and G'' (Loss Modulus) curves from an amplitude sweep on a fracturing fluid of type 2 at 20°C .

Angular frequency sweep

In Fig. 2, 3, 4, 5, 6 and 7 the storage modulus (G'), loss modulus (G''), and complex viscosity $|\eta^*|$ are plotted versus angular frequency (ω) at various temperatures. For all these measurements a constant strain of 0.1 was used. The measurements started from a high angular frequency, continuing in a decreasing order.

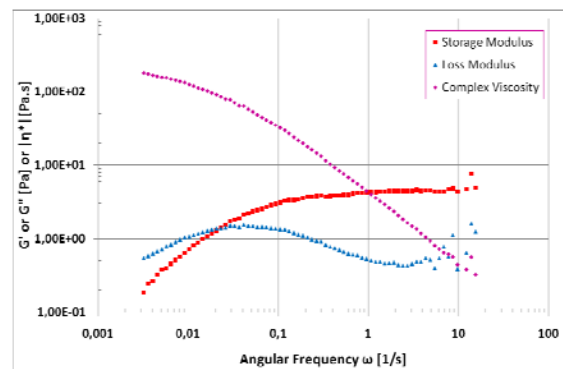


Figure 2. Frequency sweep of a borate cross-linked fracturing fluid type 1 measured at a constant amplitude of $\gamma = 0.1$ and at a temperature of 20°C .

In our figures most of the unstable measurements at the highest and lowest angular frequencies have been omitted.

In Figs. 2 and 3 are shown the values obtained for our fluids at a temperature of 20°C. From Fig. 2, showing the values obtained for Fluid 1, it can be seen that at the lowest angular frequencies the storage modulus, G' , is lower than the loss modulus, G'' . This indicates a more fluid like behavior². For angular frequencies above approximately 0.02 s^{-1} , also referred to as the crossover frequency, G' becomes higher than G'' indicating a more solid like behavior. The crossover frequency is a measure of the longest relaxation time⁵ which is the inverse of the frequency. For this fluid it was found to be 50 seconds. The plateau value of G' found when G'' is at its minimum is approximately 4.5 Pa.

The complex viscosity, $|\eta^*|$, for Fluid 1 plotted in Fig. 2 show a decreasing value with increasing angular frequencies. Towards the lowest angular frequencies we find that the curve indicates a plateau value for the complex viscosity where $|\eta^*| = \eta_0$, of approximately 32.2 Pas.

According to Mezger⁴ the shape of the G' and the G'' curves represents a fluid with widely cross-linked polymers showing a certain flexibility at rest.

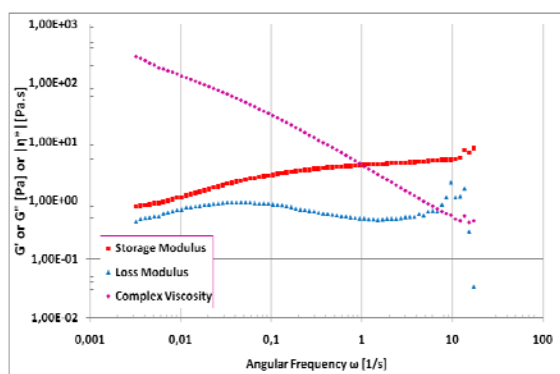


Figure 3. Frequency sweep of a borate cross-linked fracturing fluid type 2 measured at a constant amplitude of $\gamma = 0.1$ and at a temperature of 20°C.

In Fig. 3 the values obtained for Fluid 2 at 20°C are shown. For this fluid $G' > G''$ throughout the measured interval and the fluid can be said to be elastic both at long and short times i.e. low and high frequencies. Here the plateau value of the storage modulus, G_p , is found to be approximately 4.2 Pa. For this fluid, the curve showing the measured $|\eta^*|$ is not found to indicate a plateau at lower angular frequencies. Thus, this fluid is expected to behave as an elastic material at rest.

In Fig. 4 and 5 the same fluids were measured at a temperature of 50°C. For Fluid 1 shown in Fig. 4, this increase in temperature resulted in two crossover points. At the lowest angular frequencies $G' > G''$. At an angular frequency of 0.13 s^{-1} a crossover point is located above which $G'' > G'$. Then

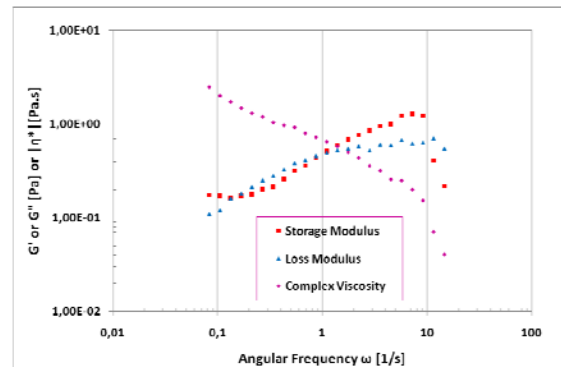


Figure 4. Frequency sweep of a borate cross-linked fracturing fluid type 1 measured at a constant amplitude of $\gamma = 0.1$ and at a temperature of 50°C.

at an angular frequency of approximately 1 s^{-1} a new crossover point is located where again $G' > G''$. At this temperature the curve representing the complex viscosity, $|\eta^*|$, is not found to indicate a plateau at lower angular frequencies.

For this fluid the shape of the G' curve towards lower angular frequencies could in accordance with Mezger⁴, be interpreted to represent a sparsely cross-linked polymer showing a low structural strength at rest, and

thus a more liquid like behaviour. A consequence could be that the drag from the fluid onto the proppants is reduced and in this way it is possible to flow back the fluid; leaving the proppants in the fracture.

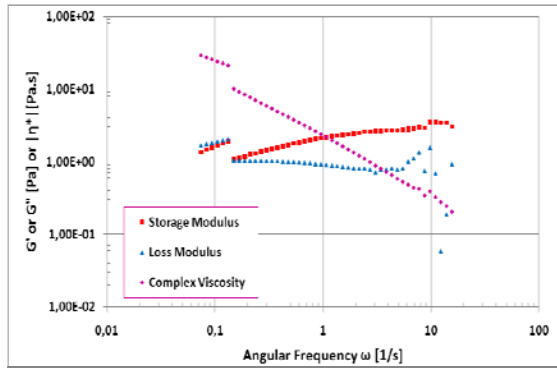


Figure 5. Frequency sweep of a borate cross-linked fracturing fluid type 2 measured at a constant amplitude of $\gamma = 0.1$ and at a temperature of 50°C.

In Fig. 5 the values obtained for Fluid 2 are plotted. As can be seen from the figure there is a sudden jump in the measured values below the angular frequency of 0.14 s^{-1} . This is expected to be due to a fault in the software as the jump was found to be similar in size for all three curves and thus, the curves are here interpreted as being continuous.

For the lowest angular frequencies we find that $G' < G''$ indicating a more liquid like behavior. At an angular frequency of approximately 0.14 s^{-1} a crossover point is found above which $G' > G''$. For this fluid and at this temperature the complex viscosity indicate a plateau value of approximately 20 Pas where $|\eta^*| = \eta_0$.

In Fig. 6 and 7 the same fluids were measured at a temperature of 70°C. For Fluid 1 shown in Fig. 6 we find that the increase in temperature from 20°C, shown in Fig. 2, to 70°C decreases all the viscosities when measured within the same angular frequency range. At the lowest angular frequencies $G' > G''$ while at higher angular frequencies $G' < G''$. This is found to be

contrary the values obtained at 20°C. Here in Fig. 6 the crossover point is shown at an angular frequency of approximately 0.13 s^{-1} . At the highest angular frequencies shown in this figure we find that there is an indication of a new crossover point where $G' > G''$. Whether this is a true crossover point or not could not be verified as for these angular frequencies and higher, the measurements became unstable; most likely because of the very liquid like behavior at this temperature.

In Fig. 6, the curve representing the complex viscosity, $|\eta^*|$, is not found to indicate a plateau at lower angular frequencies. Also in this case, as found for this fluid at 50°C the shape of the G' curve towards lower angular frequencies could be interpreted to represent a sparsely cross-linked polymer showing a low structural strength at rest. It is anticipated that this low structural strength illustrate the fluid losing its gel properties since the temperature now by far exceeds the design temperature.

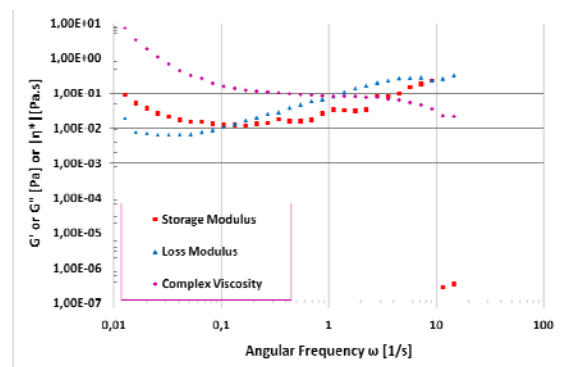


Figure 6. Frequency sweep of a borate cross-linked fracturing fluid type 1 measured at a constant amplitude of $\gamma = 0.1$ and at a temperature of 70°C.

In Fig. 7 the measured values obtained for Fluid 2 at 70°C is shown. The results, i.e. the shape of the curves, are found to be similar to that of fluid 1 at 20°C shown in Fig. 2. Thus, representing a fluid with widely cross-linked polymers showing a certain flexibility at rest while the complex

viscosity indicates the behavior of a viscoelastic liquid at rest. The crossover point where $G' > G''$ is found to be at an approximate angular frequency of 0.85 s^{-1} .

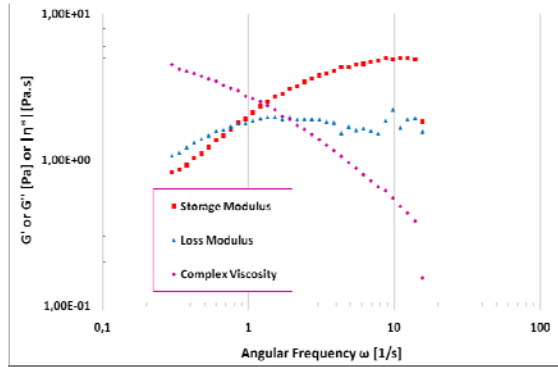


Figure 7. Frequency sweep of a borate cross-linked fracturing fluid type 2 measured at a constant amplitude of $\gamma = 0.1$ and at a temperature of 70°C .

Fluid 2 was designed for a temperature of 100°C . However, we were unable to use our measurement configuration to obtain interpretable results at this temperature. This is likely to be caused by the fluid reaching its design temperature where its properties shall be altered and by a high degree of evaporation from the fluid cell generating surface skin and other effects. Therefore, we have not discussed these results.

CONCLUSIONS

A series of rheological measurements have been conducted on borate cross-linked fracturing fluids. The measurements show that:

- The fracturing fluids are strong gels at temperatures below the design temperature.
- The fracturing fluids start to lose its gel like properties at the design temperature.

ACKNOWLEDGEMENTS

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REFERENCES

1. Economides, M. J. and Nolte, K. G. (2000), "Reservoir stimulation", Chichester: Wiley.
2. Parris, M.D., MacKay, B.A., Rathke, J.W., Klingler, R.J. and Gerald II, R.E. (2008), "Influence of Pressure on Boron Cross-Linked Polymer Gels", *J. Macromolecules*, **41**, 8181-8186.
3. England, K.W and Parris, M.D. (2010), "Viscosity Influences of High Pressure on Borate Crosslinked Gels", SPE 136187.
4. Mezger, T.G. (2006), "The rheology handbook: for users of rotational and oscillatory rheometers". 2nd Ed., Hannover, Vincentz Verlag.
5. Barnes, H.A. (2000), "A Handbook of Elementary Rheology", Howard A. Barnes, CambrianPrinters, ISBN 0-9538032-0-1.