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A Chemical Design Example of Hydraulic Fracturing Fluids in High-Temperature Hydrocarbon Reservoirs: Case Study

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Abstract

Production optimization problem in hydrocarbon reservoirs has garnered prime importance in the last few years. There are numerous methods to achieve the requisite and desired production rates. One such method is hydraulic fracturing, which has been used since the 1940s. Like many other technologies, hydraulic fracturing considers the usage of various chemicals for formulating the fracturing fluid. It has a concomitant challenge of optimal selection of such fluid as per the given conditions. The objective of this study was to validate the composition of hydraulic fracturing fluid for fracturing jobs in high-temperature Jurassic oil and gas reservoirs located in Western Kazakhstan.

A series of laboratory tests were conducted to select suitable chemicals on a scientific and practical basis. Methods used were fluid thermal stability tests, shear test and stability test - all executed on Chandler 5550 rotational viscometer. Several other tests such as emulsion break test, water analysis, crosslinking time, pH measurement and gel tests were also performed. Herein, justifications from known sources are provided alongside the enumerated laboratory tests. Thus, gelling agents, crosslinkers, breakers and various additives such as demulsifiers, pH buffers, clay inhibitors and biocides were selected. Each component has its own chemical equivalent with the desired concentration.

The formulated hydraulic fracturing fluid was successfully implemented in 20-ton hydraulic fracturing job in the Jurassic sandstone deposits with bottom-hole temperature up to 105 °C and a permeability about 3 mD. The operation was successful and resulted in production increase and promising long-lasting effects.

Keywords: Hydraulic fracturing design, Fracturing fluid composition, High-temperature well, Crosslinked gel, Fracturing fluid systems

Introduction

The products of chemical industry are used everywhere, especially in oil and gas industry. Hydraulic fracturing industry is not an exception, as the main working agent in this process is the hydraulic fracturing fluid [1], which includes a wide array of chemical additives designed for a multitude of purposes. Therefore, there are various kinds of hydraulic fracturing fluids [2-4], which are designed for diversified scenarios. As a result, there is always a need for selecting 1 or another fluid system for various hydrocarbon reservoirs.

This paper illustrates an example of fracturing fluid selection for an oil and gas field located in Western Kazakhstan and confined to the Jurassic terrigenous deposits. The properties and parameters of the reservoir and the well are succinctly presented in **Table 1**. In this study, hydraulic fracturing was applied successfully by pumping 20 tons of proppant and obtaining a 4-fold increase in oil rate. The choice fell on the hydraulic fracturing because of the presence of a high positive skin factor measured during well testing and the well potential to increase the flow rate due to fracturing operation.

The most salient characteristics of this case include (1) a high reservoir temperature of 105 °C, (2) the presence of clay minerals, (3) low values of permeability and porosity with an average permeability of 3 mD and average porosity of 10 %, and lastly, (4) the presence of the aquifer 25 m below the bottom perforations. Most of these features are decisive in a meticulous selection of the fracturing fluid.

Therefore, the aim of this study was to select the most optimal formulation of the hydraulic fracturing fluid to concurrently cope with 3 major concerns:

The fracturing fluid should perform all the necessary technological functions during the test and main treatments that include:

1) Maintaining the requisite viscosity and high shear resistance
2) Ensuring minimal frictional pressure losses in tubing
3) Keeping high carrying abilities while transporting proppant with a given concentration.

Hydraulic fracturing fluid should maximally preserve the initial reservoir characteristics to minimize the formation damage, i.e., it should:

1) Have low filtration characteristics to control fluid loss from the fracture into the formation
2) Be compatible with the formation fluid to reduce formation of stable emulsions
3) Be compatible with formation minerals such as clays to prevent swelling and pore blocks.

The fracturing fluid should be easily and quickly cleaned up from the formation during flow back operations and flow initiations, i.e.:

1) After the proppant injection is completed, the gel must break within a set period of time, which reduces its viscosity to the desired values
2) It should leave minimum residue after gel break.

To tactfully address issues above, it is imperative to simultaneously account for a number of factors and synchronize the hydraulic fracturing fluid properties by selecting the necessary components that regulate certain properties of the fluid system. Other details are explicated further in the paper.

Table 1 Reservoir and well properties.

1	Skin factor	7
2	Perforation interval	2165.3 - 2181.6 m
3	Reservoir thickness	15 m
4	Reservoir temperature	105 ℃
5	Reservoir pressure	195 atm
6	Average permeability	3 mD
7	Average porosity	10 %
8	Water saturation	30 %
9	Carbonate content	1 %
10	Petrographic description	Grey medium to fine-grained sandstone with clay cement. The rocks contain clay minerals such as chlorite, muscovite, kaolinite and biotite.
11	Presence of aquifer	25 m below from the lower boundary of the formation that is separated by a thick shale bed.
12	Tubing diameter	89 mm
13	Reservoir fluid	Oil + water
14	Production technique	Electric submersible pump

Materials and methods

Requirements for fracturing fluid with respect to technological and geological conditions

Apart from taking into account the characteristics and parameters of the reservoir and well (**Table 1**) it is also necessary to consider technological parameters of hydraulic fracturing treatment. Based on the hydraulic fracturing design the main technological conditions for fracturing fluid were identified and summarized in **Table 2**. These conditions are characterized by the values which obtained by selection of the required fluid composition.

As is known, many different fluid systems exist for different conditions. For example, slickwater, linear gels based on various polymers, crosslinked fluids, viscoelastic surfactants (VES), foams and oil based gels [3-5]. Each of these systems has its own criteria of applicability. In our case a crosslinked fluid system meets the conditions. This is justified by low (but not micro) permeabilities, available chemicals at locations, logistic infrastructure, high proppant concentrations, average treatment rates and safety concerns.

Water-based polymer system itself consists of many components that must also be selected and justified. Therefore, we selected the composition of the fracturing fluid with the required properties (**Tables 3** and **4**, respectively). Justification methods for the choice of this composition are given further.

Table 2 Required technological conditions for fracturing fluid.

No.	Parameters and conditions	Values
1	Time to perforations	3.5 min (recommended crosslinking time is 2 min)
2	Main treatment time	20 min
3	Water source	Water storage facility
4	Gel loading	Not more than 40 g/L
5	Shear test threshold	Not more than 4 s
6	Maximum proppant concentration	1,000 kg/m^3
7	Maximum treatment rate	3 m^3/min
8	Maximum treatment pressure	240 atm (at well head)

Table 3 Fracturing fluid composition.

Fracturing fluid component	Description	Concentration	
Gelling agent	Modified polysaccharides (derivatized guars)	4.8	kg/m^3
Borate crosslinker	Ulexite dissolved in diesel (40:60 %)	4.0	L/m^3
Demulsifier	25 % nonionic surfactants, 20 % methanol and 55 % water	1.5	L/m^3
Breaker	Ammonium persulfate	0.5	kg/m^3
Capsulated breaker	Encapsulated ammonium persulfate	0.1	kg/m^3
Shale inhibitor	60 % choline chloride, 0.6 % ethylene glycol and the rest is water	2	L/m^3
Biocide	Dazomet (2H-1,3,5-Thiadizine-2-thione, tetrahydro-3,5-dimethyl-)	0.01	kg/m^3
pH buffer	Sodium hydroxide	0.1	L/m^3
Basis	Water from water storage facility		

Table 4 Properties of the formulated fracturing fluid.

No.	Parameter	Value
1	Vortex closure time	20 s
2	Crosslinking time	120 s
3	Gel loading	4.8 g/L
4	Linear gel viscosity	40 cP at 20 °C
5	pH of crosslinked gel	8.7
6	Viscosity recovery time	2 s at 105 °C
7	Thermo stability time	60 min

Laboratory methods for substantiating the choice of the fracturing fluid composition

Water

Since water is the basis of the fracturing fluid its properties are considered in the first place. Water must meet the criteria specified in **Table 5**. Water from the water storage facility was tested according to API RP 45 method [6] and fully met the criteria (**Table 5**).

Table 5 Water properties for preparing fracturing fluid.

No.	Parameters	Values for water from storage facility	Limits
1	Mixing temperature	20	18 - 40 °C
2	Specific gravity	0.998	0.9 - 1.04
3	pH	7.8	6 - 8
4	Total hardness	130	Not more than 500 mg/L
5	Total iron content	1	Not more than 8 mg/L
6	Total bicarbonate content	90	Not more than 300 mg/L
7	Total chloride content	85	Not more than 1,000 mg/L
8	Total sulfate content	110	Not more than 200 mg/L
9	Total phosphate	0	Not more than 5 mg/L
10	Total mineralization	416	Not more than 2,500 mg/L
11	Total dissolved solids	130	Not more than 50,000 mg/L

Gelling agent and crosslinker

Reservoir temperature is a fundamental factor to the choice of the linear and crosslinked gel [3-5]. It determines the required viscosity of the linear gel, hence, the concentration of the gelling agent, and in addition, the type and concentration of the crosslinker. As is known, a temperature range of borate cross-linked polysaccharide-based gels is up to 150 °C [5,7]. In our case, for 105 °C, the choice fell on derivatized polysaccharide-based linear gel with concentration of 4.8 kg/m^3 (**Table 3**), that is crosslinked by a borate crosslinker with a concentration of 4 L/m^3. Such concentration of the crosslinker allows maintaining the viscosity of the crosslinked gel within the required time. It was justified by conducting a thermal stability test (**Figure 1**) which was performed on a Chandler 5550 rotational viscometer, which allows simulating bottomhole conditions, namely, keeping the temperature of the gel at 105 °C, as well as carrying out multiple measurements like shear rate, apparent viscosity and other necessary parameters simultaneously. The criterion for passing the test is the gel ability to keep the viscosity of more than 400 cP (at 100 s^{-1} shear rate) during main treatment phase which in our case is 20 min×1.2 = 24 min (here 1.2 is the safety factor). As can be seen from **Figure 1**, the test passed successfully and the gel is thermostable for more than 60 min.

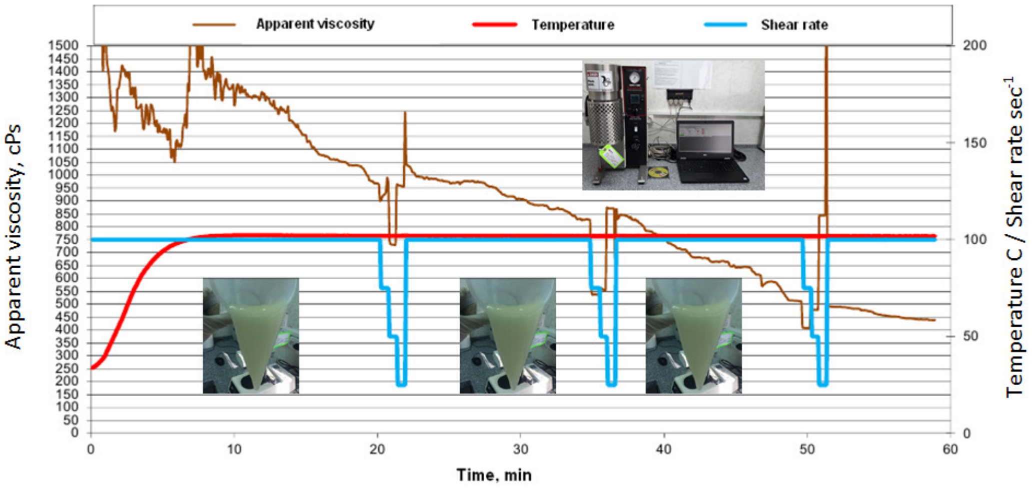

Figure 1 A thermal stability test and complete destruction of the crosslinked gel at reservoir temperature of 105 °C Chandler 5550 rotational viscometer.

A shear test on a Chandler 5550 rotational rheometer was performed in addition to the crosslinked gel thermal stability test (a shear rate of 511 s^{-1} for 5 min and 100 s^{-1} rate for 10 min at a reservoir temperature of 105 °C). The test results are shown in **Figure 2**, from which it can be seen that the crosslinked gel based on borate-crosslinked modified polysaccharides has good elasticity, strength and the ability to quickly restore rheological properties at large changes in shear rates.

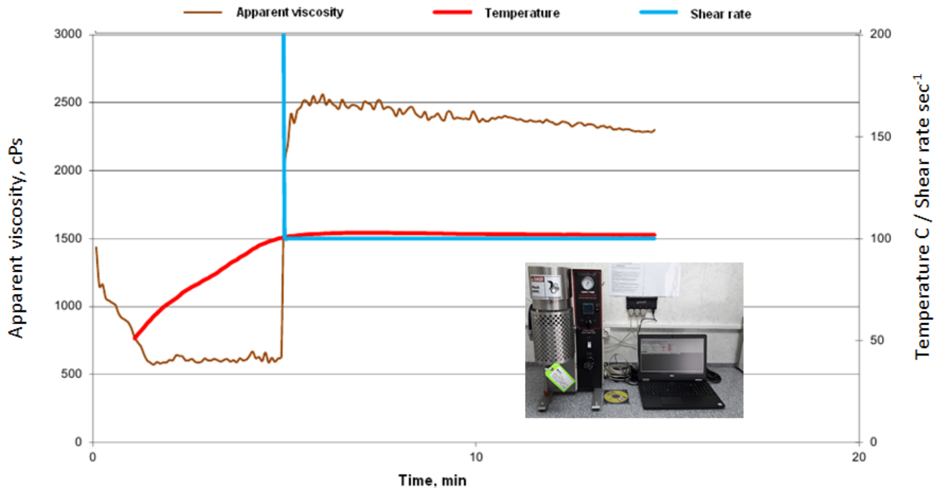

Figure 2 Shear test on a Chandler 5550 rotational rheometer (a shear rate of 511 s^{-1} for 5 min and 100 s^{-1} rate for 10 min at a reservoir temperature of 105 °C).

The next important factor is the time required for the gel to reach perforations during injection, which is 3.5 min (**Table 2**). It requires the fracturing fluid to be crosslinked not more than this time. Therefore, the recommended crosslinking reaction time was set as 120 s by adjusting the concentration of the borate crosslinker (**Table 4**). This will allow to secure the proppant transport through perforations and finally into fractures, as well as to reduce the frictional pressure losses in the tubing. In our case we used borate on the basis of ulexite, which is optimal at high temperatures and in the need of delayed crosslinking [8].

Besides the requirements of injection technology, the gel should leave minimum residue in the formation to prevent pores blocking and decrease in filtration properties [4,9]. The chosen modified polysaccharide corresponds well to this requirement. This is insured by 2 properties: Firstly, the formations of a high-quality filter cake on the fracture face, and secondly, the ability to leave a minimum residue after fracturing. Thus, the Wall Building coefficient was 9e-05 $m/min^{0.5}$, and the instantaneous spurt loss was 5 L/m^2. After gel breaks this modification should have about 6 - 10 % of the insoluble residue [10], which assumed to be an acceptable value for a formation with permeabilities of about 3 mD.

Breakers

In order to solve the problem of gel flow back after the treatment, and flow initiation it is necessary to break the gel, i.e. to decrease its viscosity. To do that, breaker with a specified properties and concentrations are used. In the meantime, the filter cake on the fracture face must also be degraded to clear the path for oil into the fracture. There are many breakers, mainly enzymes, persulfates, peroxides, bromates with various modifications for the required temperatures and pH of the environment [11]. In our case, ammonium persulfate with a concentration of 0.1 kg/m^3 was used at the main proppant pumping stages, whereas capsulated ammonium persulfate with a concentration of 0.5 kg/m^3 was used during fluid displacement stages. The choice of such low concentrations is associated with high formation temperatures, which requires delaying the destruction by these breakers.

These breakers have been tested in the laboratory. In **Figure 1**, the thermal stability test showed that the gel degrades gradually and retains its viscosity for the required time. In **Figure 3**, a gel stability test with possible errors of +20 % at breaker concentrations showed that the gel still retains its intended properties. According to the trend of the curve for 2 experiments, it can be concluded that the gel will break only after the main treatment time, which in this work is at least 20 min (**Table 2**).

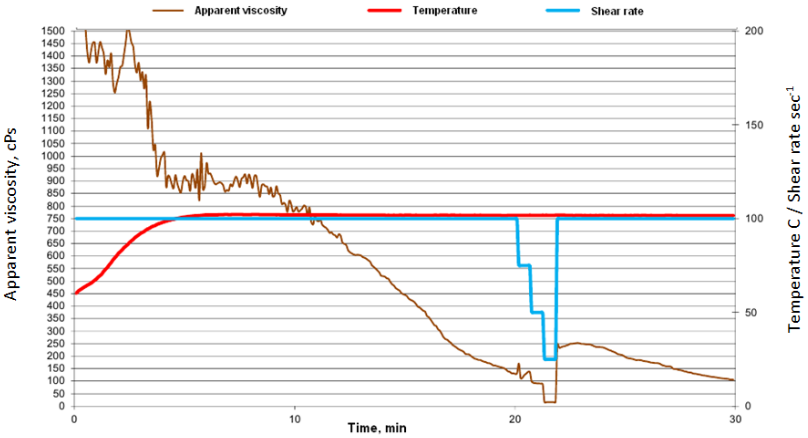

Figure 3 Gel stability test to check possible increase in breaker concentrations up to 20 % at a reservoir temperature of 105 °C on a Chandler 5550 rotary rheometer.

Additives

Additives like biocides, demulsifiers, clay inhibitors and pH regulators were added to the main hydraulic fracturing fluid.

Biocides

There are many different types of biocides today. Tetraksihydroxymethyl phosponium sulfate (THPS), quaternary ammonium compounds, glutaraldehyde, dazomet, quaternary amines, amides, aldehydes and chlorine dioxides are mostly used [3-5]. A dazomet with a concentration of 0.01 kg/m^3 was chosen for our case. It copes well with many types of microorganisms, allowing complete fracturing operations in 1 day at most (taking into account all preparation jobs).

Demulsifier

A nonionic surfactant with methanol additives was selected to prevent the formation of any emulsion of the broken gel and oil in the formation and in the fracture. After 10 min of stirring the gel and oil from the given formation complete phase separation with a clear boundary is observed, which confirms the high efficiency of using this demulsifier in concentrations of 1.5 L/m^3. Aside from that, the methanol addition stabilizes the gel viscosity at high temperatures [3,12], and also prevents the foams formation when mixing components and preparing the gel.

Such separation allows effective flow back of fracturing fluid after the treatment so that to initiate well flow. This minimizes the risk of stable emulsions forming, which can severely block the flow. In addition, surfactant demulsifiers keep the rock water wet.

Clay inhibitor

Due to the presence of clay minerals such as chlorite, muscovite, kaolinite, biotite in the formation rock, there is a need to use a clay swelling and migration inhibitor. Meanwhile, due to the presence of almost all clay minerals, the challenge is to use a universal inhibitor, which is choline chloride. For the same reasons, a high concentration of 2 L/m^3 was used here.

Buffers

Sodium hydroxide is used as a buffer liquid to regulate pH of the environment. In this case pH regulation is important, since the existing conditions of high reservoir temperature and the presence of borate crosslinkers require gel strength, which is controlled by pH ranges from 8 to 9. This allows keep the polymer concentration less than 4.8 kg/m^3 and still satisfy the requirements.

Results and discussion

On the basis of a well-selected gel, which was validated by many parameters and characteristics, successful fracturing job was carried out. As a result, the flow rate of this well increased several times after stimulation. The result of hydraulic fracturing lasted more than 1 year. The fracture was successfully created within the specified design: It had a fracture half-length of about 100 m, a fracture height of about

20 m, it was limited at the level of the perforation interval, and did not enter the water zone. **Figure 4** shows the fracture profile created by assistance of proposed fluid system. The job is assessed as successful.

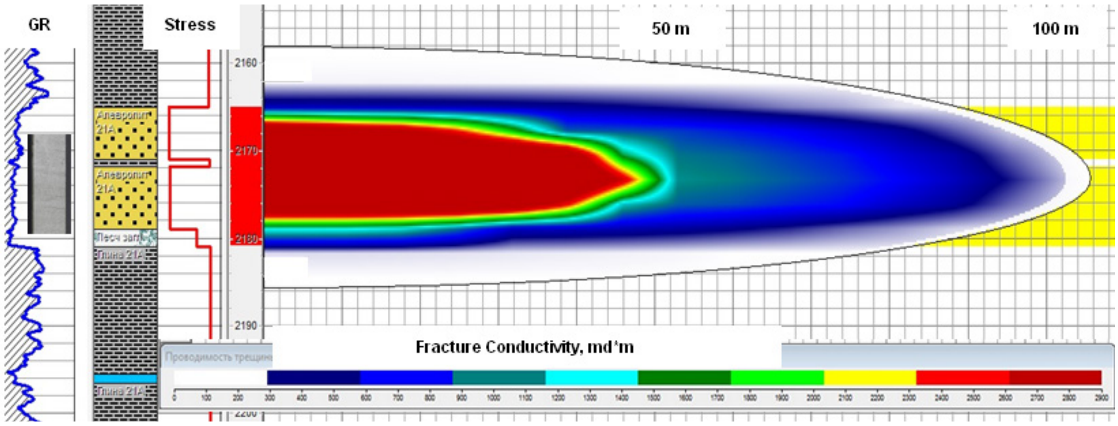

Figure 4 Fracture profile after hydraulic fracturing treatment.

Aside from the factors described above the equipment configuration was also taken into account to choose the fracturing fluid. So the number of liquid additives pumps and dry additives pumps in the blender system during main treatment limits the choice of number of chemicals. Another limitation is the equipment's transport capability to deliver required chemicals at the desired concentration. In our selection all components and their concentrations were in the range of required values of the equipment configuration.

Despite of many other factors in fracturing technology that affect the end results, the fracturing fluid is one of the most important. Therefore, the thorough analysis of fracturing fluid selection helped to carry out this job effectively.

Conclusions

This paper describes a case study selecting the hydraulic fracturing fluid composition for proppant fracturing of low-permeability Jurassic sandstones in a field located in Western Kazakhstan. Many factors have been analyzed to select the fracturing fluid, and a significant number of laboratory studies have been carried out. The followings most accurately express conclusions:

1) The optimal formulation of the hydraulic fracturing fluid was selected for operations at high temperatures of the Jurassic terrigenous formations, in particular at 105 °C at depths of more than 2,000 m. A water-based crosslinked polymer gel system was chosen in the role of the fracturing fluid. Borate crosslinked modified polymers were used as a gelling agent. The gel was destroyed by ammonium persulfate. The control of the remaining required properties was carried out by adding clay inhibitors, pH regulators, biocides and demulsifiers.

2) Many factors that effect on the fracturing fluid properties and parameters were taken into account during selection. Namely, proppant pumping technology, well parameters, water properties, properties of the formation rocks and formation fluids, as well as equipment configuration.

3) Despite of the fact that the hydraulic fracturing fluid selection is a routine work during the fracturing design, considerable attention was paid for the optimal selection of the fracturing fluid composition so that to contribute to the successful treatment. A comprehensive approach has been implemented and resulted successfully with obtaining an optimal fracture and a corresponding increase in well production.

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