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Development of a novel chemical water shut-off method for fractured reservoirs: Laboratory development and verification through core flow experiments

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ABSTRACT

Most of the extended reach horizontal wells and also the vertical wells with permeability heterogeneities often experience premature and excessive water production from multiple, high permeability streaks and conductive fractures. Bullhead and Relative Permeability Modifier (RPM) treatment often fails to achieve the desired result, as in most cases the situation warrants isolation and protection of the oil producing zones, from highly damaging polymeric gels. Protection of oil zones in a highly fractured reservoir is technically and economically a huge challenge because of knowledge on the complexity of fracture network. This paper describes the application of three chemical fluid compositions in sequence, as an alternate rigless water control option whose self-selectivity and effectiveness in controlling water production are verified in the laboratory in simulated fractured reservoir condition. The first fluid is designed to protect the matrix by creating an impermeable filter cake on low permeable oil saturated zones, keeping the water swept fractures open for gel treatment. The second fluid is a cross-linkable polymer gelant to shutoff the fractures and the third fluid is an enzyme breaker for cleaning the filter cakes form matrix zones. After completion of the treatments, return permeability measurement was carried out which shows 85–90% reduction of water permeability with less than 15% reduction of oil permeability. Microscopic investigations on treated core plug show very little invasion of polymer gel into the matrix area, whereas the fractures are almost completely sealed. The technology could be suitably applied without rig deployment and at a low cost. However, the fluid composition, pumping pressure and flow rate need to be customized based on the candidate well and the actual reservoir parameters.

1. Introduction

In mature oil fields, high water cut production has always been a common but difficult problem. This has been more pronounced with advent of extended reach drilling and multilateral wells. Often these wells pass through multiple conductive fractures, faults and high permeable streaks connecting the wellbore to the under laying aquifer or injection water front and the mobility advantage results in high water cut production. Unless completed with intelligent/smart technology with the choice of flow control/shutting down individual lateral/well segment, controlling excess water production could only be achieved through chemical (polymer gel) or mechanical means.

The success of polymer gel application in controlling water has largely been limited to vertical wells and short horizontal wells with fairly well known reservoir characteristics. In the more complicated reservoir with long horizontal legs, there are additional challenges like (a) identifying water conductive zones and (b) placing adequate volume of right type of gelant and most importantly (c) protecting the oil bearing zones from invasion of almost irreversibly damaging polymer gel.

In reservoirs where numerous conductive fractures or high permeable thief zones are naturally present, identification, isolation and protection of oil bearing zones from gelant invasion are technically and economically not feasible. A number of different approaches have been suggested in literature to tackle these challenges. However on field trial, most of them were found to be ineffective. The common misconception that water-based polymer gelant would preferentially enter water flooded zones much more readily than high oil saturated zones, have been analyzed in detail and showed that except for reservoirs with high oil/water viscosity ratios ($>$ 100), gelant penetration distance into high oil and high water saturated zones will not be much different (Liang et al., 1993) . Bullheading of cross-linked polymer

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gel has largely been unsuccessful in a number of fractured reservoirs. Although water production is reduced, oil production is reduced too, in most cases (Johnson, 2001; Turner and Nwaozo, 2010). Some polymer gels that reduce K_w much more than K_o (popularly known as Relative Permeability Modifier or RPM) were seen as advantageous for blind and bullhead treatment (Lewawt et al., 2005; Liang et al., 1993). The scopes and limitations of RPM application and bullhead treatment have been summarized (Sydnask and Seright, 2006). It was observed that the RPM chemistry could not be exploited in all cases as most reservoirs are sensitive to increased irreducible water saturation due to polymer adsorption, which reduces endpoint oil relative permeability (Zaitoun et al., 1991). Awad et al. (2010) emphasized the necessity of accurate pre-treatment reservoir parameters for screening right candidate well and designing RPM job, for successful RPM application, which is difficult to obtain in majority of cases. Difference in formation pressures between high and low-permeability zones, when the zones are separated by an impermeable barrier and when the formation pressure in the low-permeability zone is significantly higher than that in the high permeability zone, could be exploited with selective placement of gel by injecting at a pressure higher than the high permeability zone but low enough not to exceed the formation pressure of the low-permeability zone. However this is not the case when water movement is through fracture or high permeability thief zones without zone separation (Seright, 1995). Application of foam gel is the only technology reported in the literature with successful water control and improvement of oil production rate in fractured reservoirs; however these cases are confined to Chinese oil fields only (Qing et al., 2009; Wang et al., 2008).

In this article, laboratory development of a novel rigless, self selective, water shutoff technique is presented, in which three well treatment fluids are designed, refined and pumped through fractured core plugs in sequence. The first fluid, containing suspended micro-fibrous particles is a viscous solution, to be pumped to create an impermeable filter cake on the low permeable oil bearing zones but allow further passage of fluid through the fractures. This technique would rely on the difference between the particle size of the suspended materials, the pore throat size distribution of oil bearing matrix zone and fracture aperture. The particle size of the fibrous materials is carefully selected, to be small enough to penetrate freely through the fractures, but large enough to form an external filter cake on the matrix zones. The second fluid is a cross-linking polymer gelant, which would be injected immediately after the first fluid, at a pressure less than formation fracture pressure. The gelant would penetrate and seal only the fractures, because the low permeable matrices are already protected by the impermeable filter cake of the first fluid. It is also essential that the filter forming materials and gelant polymers should be removed from the wellbore, to gain sufficient return permeability and well productivity. An enzyme based chemical breaker solution (the third fluid) is evaluated for this purpose. The treatment and flow studies are conducted in a high pressure-high temperature core flow set up. The extent of external and internal damages after the treatment is studied through optical and scanning electron microscope to provide an insight of wellbore cleaning efficiency.

2. Experimental design

2.1. Porous media

Berea sandstone core plugs of 100–200 mD permeability range were cleaned and their absolute brine permeability (K_{wabs}), effective oil permeability (at S_{wirr}) and effective brine

Fig. 1. Point load tester used for fracturing core plugs. Core plug top face of the fractured core plugs-A, B and C.

permeability (at S_{or}) were measured. Core plugs A and B were fractured longitudinally into two halves with the help of a point load tester to create small to medium fracture. The core plug was carefully placed and centered between the base plate at the bottom and the pointed tip at the top and pressure was applied gradually, till the core gave in and broke into two halves (see Fig. 1A). Core C was intended for creating a wider fracture and cut by a diamond core cutter into two halves. To create low, medium and high aperture fractures, sand grains of different sizes were placed and heat shrink technique was used to combine them together. Photo of the final test core plugs can be seen in Fig. 1B. The petro-physical properties along with the fracture aperture data of the whole cores and fractured cores are given in Table 1. Mineralogy, determined by XRD revealed quartz as dominant mineral, anhydrite as minor and kaolinite as fine clay in traces. Optical stereo microscope (OSM) was used to determine fracture width and scanning electron microcopy (SEM) helped to determine pore throat sizes.

2.2. Fibrous suspension for matrix protection (Fluid 1)

This fluid is designed to create impermeable barrier on the matrix surface, keeping the fractures open for polymer gelant invasion. The envisaged required properties of the fluid 1 are (a) the suspended fibers should be small enough to flow freely through the high perm fractures, (b) be large enough not to enter the matrix area but able to create an impermeable filter cake (c) should have a narrow particle size distribution (d) should be easily degradable by suitable chemical breaker in order to gain return permeability of oil bearing matrix, close to original. With this view, carefully selected micronized cellulose fiber of 100 to 200 μm (in aqueous medium) was mixed with xanthan polymer (XP) solution of optimum viscosity. The final composition of fluid