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IMPROVING STIMULATION RESULTS IN SHALY SANDSTONE RESERVOIR AFTER INVESTIGATING RESERVOIR CHARACTERISTICS: A REVIEW

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A B S T R A C T

World oil reserves increased rapidly during the decade of 80s due to improved recovery techniques. Stimulation and hydraulic fracturing played a key role in those techniques used to enhance recovery. Stimulation is a sensitive technique to improve production and ultimate recovery, but stimulation of clastic reservoirs is a tedious job due to complex mineralogy of matrix rocks and cement, compared to carbonate rocks. A multidisciplinary approach is essential to stimulate clastic rocks for getting required results. Petrography is one of the vital tools to interpret minerals, but this is not sufficient to identify minerals composing rocks. Experimental study was conducted to observe the reaction of mineral presets in rocks and stimulation fluids under microscopes. The objective of the study was to highlight the sensitivity of different minerals present in rocks. Petrography and X-ray Diffraction information about composition of sandstone rocks (mineralogy) was obtained in laboratory and this paper mentions the sensitivity of these grains with stimulation fluids of different rates. Mostly sandstones are dominantly composed of Quartz (SiO_2), subordinating feldspars (($KAlSi_3O_8$ – $NaAlSi_3O_8$ – $CaAl_2Si_2O_8$) and lithic fragments (sand size fragments of pre-existing rocks). Quartz grains are highly resistive to 15% hydrochloric acid as compared to calcite, carbonaceous, carbonate, minerals. HCl reacts with carbonate and carbonaceous quickly to enhance near borehole permeability. Besides this, when iron minerals (mostly in red color sandstone and act as cement) react with stimulation fluids caused precipitation and permanent damage to the reservoir. Therefore, petrographic information is vital in designing stimulation jobs to minimize formation damage by identification of sensitive minerals to stimulation fluids.

Keywords: stimulation shaly; sandstone reservoir; petrography mineralogy; formation damage.

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Introduction

Sandstone reservoir stimulation is difficult job due to variable mineralogical composition and presence of shale or argillaceous material, makes more challenging. Knowledge of reservoir mineralogy has strong effect in designing and planning of stimulation jobs. Although sandstone reservoir stimulation began in the early 1860s [1] and has steadily improved over time, it remains a challenging task. Few papers mentioned first acid stimulation job was conducted in 1895 by Harman Fraesh of Standard Oil Company [2]. Purpose of stimulation is to enhance production from the reservoir by improving flow path after removing formation damages caused by drilling fluids, completion fluids, stimulation fluids, increasing relative permeability by dissolving certain cement minerals. Contrary to carbonate rocks, sandstone composition varies in different sandstone reservoirs matrix as well as cement, especially when having shales. Rock forming minerals also reduces permeability especially as cementation in rock by quartz overgrowth, or presence of iron minerals or clays. Recent laboratory experiments proved oil displacing agents. Recent laboratory experiments proved the injection of bioreagents into a reservoir resulted in the creation of oil-displacing agents along with a significant amount of gas (carbon dioxide, CO_2) in oil reservoirs [3, 4]. This method was applied in Zhetybai Field (Kazakhstan) to evaluate sweeping efficiency of the area in carbonate reservoir.

Stimulation techniques for clastic rocks developed in 1935 and advanced significantly by using different solvent and retarders and their combinations to avoid formation damages. Sensitivity of fluid reactions to different minerals of rocks increase at high-temperature reservoirs (workers mark high-temperature reservoirs limit as 200 °F [5]. Different minerals have different sensitivity with different stimulation fluids but high reaction rate with combinations of acids yielding more quantity of precipitates hence chance of formation damage increased manifolds. This paper critically reviews reaction, rate of reaction, precipitation and proposed a modified recipe for stimulation for shaly or argillaceous sandy reservoirs.

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Methodology

This section describes presence of minerals in sandstone reservoir by petrographic studies and analysis of clays along with minerals major minerals by X-ray diffraction. These rocks are evaluated with different reagents for the reactions under plain light at X10 magnification. These regents were 10% hydrochloric acid (HCl), hydrofluoric acid (HF), acetic acid (CH_3COOH), toluene (C_7H_8), ammonium chloride (NH_4Cl), alcohols like methyl-ethyl-glycol (MEG) [6, 7] Its account is given in the following lines.

Petrography: Mineralogical composition of reservoir rock studied under crossed-Nicol polarized microscope to identify minerals, matrix, and cement [7]. Thin sections of flush cuttings of sandstone were prepared by using blue epoxy impregnation and studied in polarized light under 40X or 60X magnification by using Olympus BX51 Fluorescence Microscope. Mineralogical composition was quartz, with subordinating lithic fragments, carbonate, mica schists and glauconite, cemented with quartz overgrowth, shaly and ferruginous material. Lithic fragments are well packed quartz grains and ferruginous material, which is filling pore space as cement. Quartz grains are anhedral, with overgrowth due to pressure solution this quartz overgrowth is also forming cement (fig. 1).

However, matrix also includes quartz and calcite grains with some mafic grains could be solid hydrocarbon. Drill cuttings almost composed of all quartz. These quartz grains are bounded with silica cement form due to quartz overgrowth. In few cutting grains reddish brown ferruginous substance is also acting as cement. Then these samples were treated with different solutions to observe reaction with matrix and cement in rocks. These samples were treated with hydrochloric acid of difference concentrations (10% and 15% conc.), hydrofluoric acid, xylene, acetic acid, sodium hydroxide ammonium hydroxide and with different compositions and ratios of above fluids. Photomicrographs of reacted rocks were also taken and studied at X60 magnification (fig. 2).

XRD Data: X-ray diffraction (XRD) analysis was also conducted to confirm mineralogy of the sandstone part of reservoir. Siemens D-5000 X-ray diffractometer machine was used to scan bulk reservoir powder samples. These samples were grinded after drying it in oven at 100 °C for 12 hours. Grinding of samples was conducted in agate mortar up to 200 meshed sieve size. About 0.75 gram of un-oriented sample powder was compressed in holder to scan. Interval was selected between 2° to 4° with scanning speed 8°/minute and sample interval of 0.2°. Diffractogram is given in figure 3.

Quartz is the most dominant mineral. Major quartz peak is recorded at 26.62° and other peaks are noted at 20.85°, 36.52°, 39.52° and 50.2° at 2θ. Other minerals are identified on the diffractogram are siderite and the highest peak of 2θ of Quartz (26.62°) following by 20.8° of Quartz albeit with their 2θ of 32.07° and 27.79°. Among the clay minerals illite and kaolinite are present. Both minerals are also identified on 9.86°, 25.15°, 12.39° and 12.39° at 2θ, respectively.

Experimentation and laboratory work/study of shaly sandstone and stimulation fluids under microscope

Shaly sandstone reservoir stimulation is complex process due to multiple minerals and their sensitivity with different chemical fluids. Studied sandstone part of reservoir rocks is composed of quartz, feldspars, albeit glauconite, siderite etc. are also identified in thin sections and x-rays diffraction at 2θ as 9.86°, 25.15°, 12.39° and 12.39°, respectively. Treatment of sandstone within reservoir is for production improvement by enhancing permeability, by removing the formation damage and removing extent of damage that reduces production [8]. These parameters determine the characteristics of the treating fluid; the technique used to reach and remove the damage area by using diverter. Various parameters effect the efficiency of stimulation fluid such as reservoir heterogeneity, return, leak of test [9, 10].

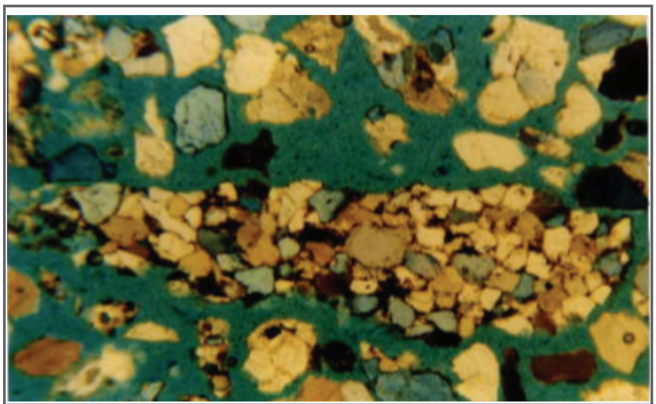

Fig. 1. Middle part of the photograph (60X) is showing quartz grains are cemented with ferruginous material whereas in upper part of the photograph quartz grains are cemented with quart cement. Isolated sand grains are showing quartz over-growth

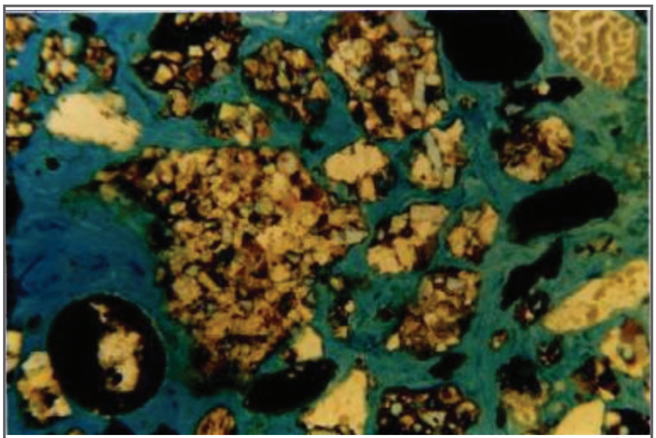

Fig. 2. Flush cutting's micrograph (60X) indicated ferruginous cement (center) and silica cement (right side)

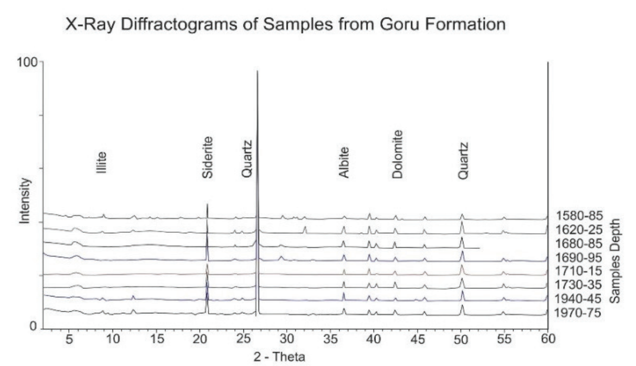

Fig. 3. XRD diffractogram showing highest peak of 2θ of quartz (26.62°) following by 20.8° of quartz

Rock cutting of reservoir sections reacted with different chemicals, part of stimulation fluids of variable concentrations such as 5 and 10% hydrochloric acid (HCl), 3% hydrofluoric acid (HF) and 5%, and their different composition, 10% acetic acid (CH_3COOH), 5% toluene ($C_6H_5CH_3$), 1-10%, ammonium chloride (NH_4Cl), alcohols like 10% methyl-ethyl-glycol (MEG) to observe their reaction. Other chemicals used in preparation of stimulation fluid such as silt remover, shale stabilizers, chemical diverter, iron control agents etc.

Reaction with hydrochloric acid (HCl)

Hydrochloric acid (HCl) dissolves calcium carbonate ($CaCO_3$) and siderite ($FeCO_3$) minerals as observed in laboratory but it was reacted with 10% HCl but slowly reacted with 15% HCl. It was observed that HCl concentration depends upon mineral composition, permeability, temperature, and pressure. Figures 4a and 4b are showing 10% HCl only cleans grains without any dissolution. HCl concentration depends upon fines in rocks. Field experience indicates that lower volumes of HCl are adequate to wash the rocks around bore hole walls. Acid concentration increases dissolution resultant into precipitation. Figure 4b indicates precipitation of soluble minerals in 15% HCl. Soluble minerals are feldspar and grains of carbonates.

Acid concentration is not a straightforward it is dependent on mineralogy, porosity, permeability. The principal role of hydrochloric acid is to prevent secondary precipitations by maintaining a low pH value. In the case of a feldspar having sodium, calcium, and alumina and reaction rate with mud acid mentioned in equation given below:

$$\text{Feldspar dissolution rate} = 1.3 \times 10^{-9}(1+0.4[H^+])\,[HF]\ (\text{moles/feldspar/cm}^2\text{/s}) \quad (1)$$

Solubility of minerals in sandstone is strongly depending on the position of mineral either it is grains or cement, therefore petrographic studies are useful for effective stimulation of reservoirs.

In most cases 20% HCl is used for pre-flush to avoid any contact between other reactive minerals such as carbonate. As it is well known that sandstone always contains argillaceous or clay material. In our case illite [Si_4-x Alx O_{10} $(OH)_2$ Kx Al_2]

a)

b)

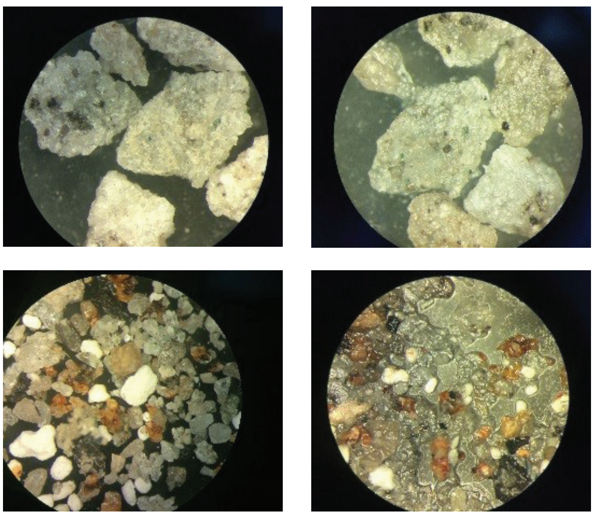

Fig. 4. a) Reservoir sandstone grains prior to reaction (left), reaction with HCl 10% at normal room temperatur (right), b) reservoir grain prior to reaction (left), sample after reacting with HCl 15% (right)

clay is present as reported in X-ray diffraction. The formation damage could also result due to interactions of different minerals (siderite) present in the sandstone rocks with the different injected fluids [11].

Reaction with hydrofluoric acid

Major constituent of sandstone is quartz (SiO_2) and it is always considered as slow reacting mineral with other acids. It reacts slowly with HF, whereas feldspars are fast reacting minerals are considered and that is not present in the reservoir. Silica reacts only with hydrofluoric acid because fluoride (F’) ion [12] as given below in equation 2 [13].

$$4HF + SiO_2 \leftrightarrow SiF_4 + 2H_20 \quad (2)$$

HF is a weak, highly corrosive acid due to its low ionization in water. HF, or more usually HF-releasing chemicals such as ammonium bifluoride (NH_4HF_2), is used for sandstone matrix acidizing, combined with hydrochloric (HCl) or organic acids. The combination of HF and HCl is also known as «mud acid», usually used to remove mud particles to clean reservoir sandstone. Minerals can be categorized based on their reaction rates into slow and fast-reacting types. Quartz reacts more slowly, while feldspar and clay exhibit faster reaction [14]. Chemical reactions during acidizing took place in multi stages, first is slow that may damage reservoir by reducing porosity and permeability caused by precipitation.

(i) Precipitation of hydrated silica:

$$4HF + SiO_2 = SiF_4 + 2H_2O \quad (2)$$
$$SiF_4 + 2F = SiF_6 \quad (3)$$
$$SiF_6 + 2H_2O = H_2SiF_6 + 2H_2O \quad (4)$$
$$H_2SiF_6 + 4H_2O = Si(OH)_4 + 6HF \quad (5)$$

(ii) Precipitation of sodium, sodium silicates, potassium, potassium silicates, and calcium, calcium fluoride:

$$H_2SiF_6 + 2Na^+ = Na_2SiF_6 + 2H^+ \quad (6)$$
$$H_2SiF_6 + 2K^+ = K_2SiF_6 + 2H^+ \quad (7)$$
$$2HF + Ca^+ = CaF_2 + 2H^+ \quad (8)$$

Sandstone acidizing takes multiple stages of fluids and reaction of these fluids with the minerals in porous media. At high temperatures, these reactions cause precipitations.

These reactions can cause formation damage (eq. 3), (eq. 4) and (eq. 5), HCl or other organic acid is used in the main acid stage to avoid any damage. To avoid reactions (eq. 6), (eq. 7) and (eq. 8), ammonium chloride or HCl is acid is used as a pre-flush pumped ahead of the main acid, which usually contains HF acid. Sodium and potassium are released in reaction with feldspars [15]. Sandstone matrix acidizing is a well stimulation technique designed to improve permeability by dissolving damaging minerals and fines in the formation. 15% HCl is making more precipitation rather than cleaning or washing away these precipitates. Experiments series performed to observe results under microscope.

Solubility test and stimulation test were carried out by action with 10% HCl, 15% HCl, 3% HF (12% HCl : 3% HF), 5% HF (20% HCl : 5% HF), 5% toluene, 10% acetic acid and ammonium chloride (NH_4Cl). These tests were conducted on flush cuttings of different sands of the reservoir at normal room temperature and pressure under the same conditions. The effects of reactions were observed under microscope at 40X magnification. About 108 samples were taken from more than 200m thick sand-shale sequence with no drastic change in reservoir mineralogy vertically or spatially in reservoir and reacted with different chemicals [11]. When siderite ($FeCO_3$) reacts with hydrochloric acid (HCl), it produces carbon dioxide gas (CO_2), water (H_2O), and dissolved iron ions (Fe^{2+}) as the primary reaction products, essentially dissolving the siderite mineral due to the acid's reaction with the carbonate ion; the chemical equation for this reaction is:

$$FeCO_3+2HCl=FeCl_2+H_2O+CO_2$$

When limestone ($CaCO_3$) reacts with HCl, it produces calcium chloride ($CaCl_2$), carbon dioxide (CO_2), and water (H_2O). This is a double displacement reaction, where two compounds exchange ions to form new compounds.

$$CaCO_3+2HCl=CaCl_2+CO_2+H_2O$$

Reaction with other acids like nitric or sulfuric acids do not have ability to react with silica but hydrochloric acid reduces precipitation product during reaction [12].

Reaction with combination of hydrofluoric acid:

In laboratory reservoir sand treated with 3 and 5 % fluoric acid (HF) with combination of hydrochloric acid 10%. It was to observe precipitation of insoluble and soluble product resulting in reaction. These soluble products are fluorides of different elements that reacted with HF e.g., sodium or potassium hexafluosilicate (K_2SiF_6) in formation brines with solubilized species. Silicon complex (SiF_4) is not stable in aqueous solutions therefore silica dissolution consists of the chemisorption of the fluoride anion at the silica cation at surface [13]. On other hand, this is mentioned that fluoride anion that absorbs hydrogen and other gas is formed [16] i.e., silicon tetrafluoride due to reaction of HF with SiO_2. This reaction is dependent on temperature and pressure conditions .

Reservoir sandstone samples were treated with 3, 5 10, and 20 % hydrofluoric acid. It was observed sandstone slowly reacted with 12% HCl: 3% HF but strongly reacted with 20% HCl: 5% HF and quartz grains formed precipitations but rock fragments and siderite grains showing poor impact of acid. Two types of reactions were recognized with sandstone and HF, first is within bore hole, near bore hole in which stimulation fluid dissolves more favourable minerals like feldspar with HF 3% Sample post reaction with HF 3% showing precipitates of dissolved mineral or residue shows higher rate of reaction and more precipitation of mineral grains and clays [17]. Second reaction away from the bore hole deeper in the reservoir by reacting with quartz, siderite etc (fig. 5).

Reaction with acetic acid

Acetic acid (CH_3COOH) 10% acts in stimulation solution as stabilizer but it does not react with reservoir rocks. Although acetic acid substitutes for HCl at higher temperature more than 204 °C. It is used to control precipitations of carbonates that formed due to HCl and HF. Depending on the bottom-hole temperature, different organic testers are used as when methyl format between 130 and 180 °F (54 and 82 °C), with the reactions (as presented following equation).

$$HCOOCH_3+H_2O=HCOOH+CH_3OH \qquad (9)$$

Whereas at slow rate-controlling reaction presented as in the equation given below in equation 10.

$$HCOOH+NH_4F=NH_4^++HCOO^-+HF \qquad (10)$$

Displace brine from the wellbore when an ammonium chloride spacer is not used, to avoid contact between Hydrofluoric and any formation brine containing potassium, sodium and calcium. Following photographs showing flushing of grains after application of acetic acid. Acetic acid is non-reactive with siderite and $CaCO_3$ at room temperature (fig. 6).

Reaction with toluene

Strong hydrocarbon solvent 5% toluene (C_7H_8) is used to clean borehole from paraffin and asphalting main job (fig. 7). These are used along in combination with hydrochloric acid or ammonium chloride. No significant reaction with sandstone is observed under microscope. Other additives such as surfactants, clay stabilizers and complexing agents combined with toluene or xylene in concentrations of 1 to 10% (vol/vol). Its composition depends up on temperature of formation, adhesion, and hardness of organic deposit. These chemicals are used to clean up tubing and completion by soaking for

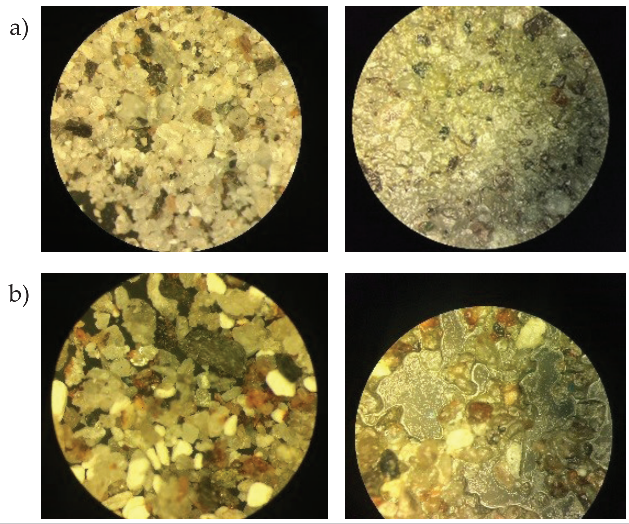

Fig. 5. a) Reservoir sands sample prior reaction with HF 3% (left), sample post reaction with HF 3% showing recipitates of dissolved mineral(right), b) sands sample prior reaction with HF 5% (left), residue shows higher rate of reaction and more precipitation of mineral grains (right)

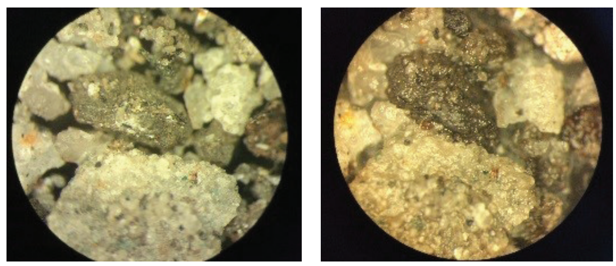

Fig. 6. Sample prior reaction with acetic acid 10% (left), sample after reaction with acetic acid 10% (right)

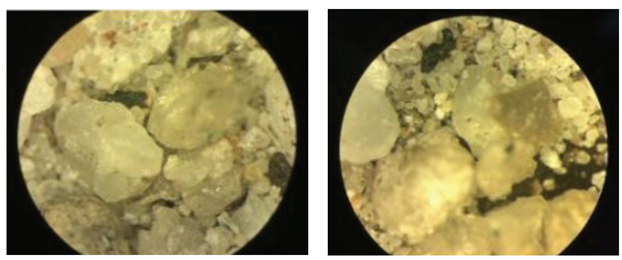

Fig. 7. Rock sample prior to reaction with toulene (left), after reaction with toulene (right)

hours followed by washing action. The content of xylene or toluene are depending on the type, hardness, adhesion, and temperature of the deposit. For matrix, wellbore and tubing cleanup treatments, a soaking period of several hours, followed by a washing action, is recommended before returning the well to production.

Reaction with ammonium chloride

Reaction with ammonium chloride sandstone rocks is commonly stimulated with mud acid that is mixture of hydrochloric and hydrofluoric acid in variable proportions. These compositions are diluted by reacting with ammonium bifluoride with hydrochloric acid. Ammonium chloride is used as retarder to achieve sufficient acid penetration around the wellbore, especially in high-temperature wells. Precipitation of hydrofluoric acid by-products too closed to the borehole, avoiding another formation damage (fig. 8).

Moreover, ammonium chloride stabilize fine particles to avoid any formation damage. Reaction of ammonium chloride with rock cuttings is observed by using 1 to 10 % (v/v) concentration of ammonium chloride. 3% ammonium chloride brine proved most effective for cleaning and retarder. Although high pH acidizing system are not recommended in high temperature bore holes and are used in borehole up to 360 °F (182 °C).

Ammonium chloride also provide a buffering effect of an organic acid and its ammonium salt, mixed with ammonium fluoride, as a hydrofluoric acid precursor. Other buffered systems are formic acid/ammonium format with pH value equal to 3.5 to 4 acetic acid/ammonium acetate and citric acid/ammonium citrate with pH value equal to 4.5 to 5. Acid system applicable for moderate to deep penetrations by many workers [18, 19]. They used a phosphoric acid complex.

(HEDP) to hydrolyzer (NH_4HF_2) instead of HCl. HEDP has 5 hydrogens available that dissociate at different stoichiometric conditions. Mixture of HEDP acid with NH_4HF_2 produces an ammonium phosphonate salt and HF.

Reaction with methyl-ethyle-glycol (MEG 5%)

A combination of alcohols is used to avoid fluid loss in the reservoir. A mixture of methyl-ethyl-glycol (MEG) are used to reduced fluid loss in the formation by lowering surface or interfacial tension mostly in gas wells. Such aqueous solution contains MEG from 10–60 % alcohol in the solution but in laboratory 10% solution was used that is suitable for the reservoir under discussion. Methanol also used as surfactant to reduce surface tension to avoid water losses in gas bearing reservoir. Beside this MEG also helps in removing of paraffin or asphalt. In low permeable sandstone many authors [6] mentioned for use of MEG as a component of water and acid based fracturing fluids [8] as temperature stabilizer because it acts as an oxygen scavenger. Polymers are available that will viscosity pure methanol or isopropanol.

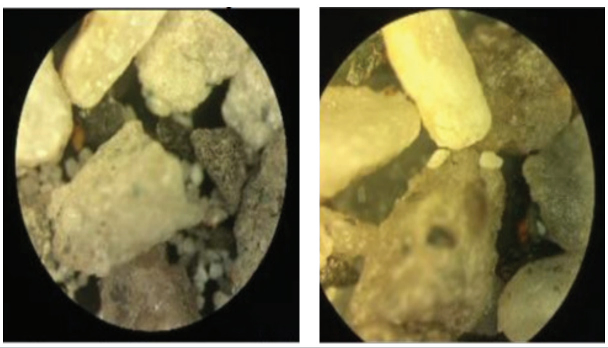

Fig. 8. Rock sample prior to reaction with ammonium chloride (left), after reaction with ammonium chloride (right)

MEG helps in reducing mineral and acid reaction by playing retarder role. Main objective of acid job is to increase porosity and permeability and HCl and HF acids reacts deep in rocks quickly. MEG also helps to slow down reaction to avoid any emulsification, and reaction with any organic rock. Iron minerals dissolution and precipitation also reduced with the application of MEG and this solution used after flushing stage to restore formation wettability [8]. Sands were treated with MEG but not apparent reaction is noted due to absence of any organic material. On contrast to acid its reaction is uniform despite of cutting size vary greatly.

Supporting chemicals

Maximum cleaning of new borehole is required before acid job therefore dispersed silt and other particles present in reservoir are removed. Silts and clays are present in 3-5 feet around borehole. Various stabilizers are sued to avoid its damage to react with HF acid. Dilute HCl is used to remove these particles. Organic acids (e.g., lactic acid, acetic acid, formic acid, etc.), ammonium acetate or formic acids are used to protect corrosion from damaging action of HF. In long sections or selective perforations chemicals are used to divert stimulation fluid to tight part of the reservoir. Sodium benzoate reacts with HCl and produce is benzoic acid as:

$$C_6H_5COONa + HCl = C_6H_5COOH + NaCl$$

Chemical diverters can be used in sandstone, to equalize the flow between different zones by building cakes with good porous zones to distribute stimulation fluid in the layers of different porosity and permeability.

Discussion

Stimulation is one of the most effective techniques for enhancing production in sandstone reservoirs by removing fines, dissolving cementing materials, and improving near-borehole permeability. However, this process is complex and requires a precise approach, as there is no universal solution applicable to all sandstone reservoirs. The key to successful stimulation lies in understanding the mineral composition of the rock and its interaction with various chemicals, reaction rates, and precipitation tendencies while avoiding formation damage. Many new techniques are also introduced such as gasified acid, bioreagent with CO_2, to enhance production but still in development phase [5, 6, 20].

Sandstone stimulation involves two critical phases: job design and job execution. The design 25+ focuses on selecting appropriate acid formulations, typically involving mud acid [21] (a mixture of hydrochloric acid (HCl) and hydrofluoric acid (HF)). In sandstone formations containing less than 6% calcite, a commonly used mixture is 12% HCl and 3% HF, as it effectively dissolves fines without excessive precipitation [22]. However, the presence of iron minerals in the reservoir matrix significantly increases the sensitivity of the reaction and must be carefully considered [23].

The reservoir under discussion comprises shale, quartz, feldspar, siderite, calcite, and glauconite. The reaction rate of HF with these minerals depends on multiple factors, including rock composition, surface area, and borehole conditions (pressure and temperature) [22, 24]. HF reacts in a first-order manner, where the reaction rate is directly proportional to acid concentration and the area-volume ratio [24]. Observations under a microscope over 120 minutes under static conditions show that calcium fluoride (CaF_2) precipitates, which can damage the formation. Although quartz grains themselves are highly resistant to acid, the binding materials comprising feldspar, iron minerals, clay, and carbonaceous material are vulnerable to acid reactions. Precipitated materials may migrate toward the flow path and cause blockages near the borehole, reducing porosity and permeability. As already mentioned, that acid-induced precipitation can occur in two primary ways; (i) Precipitation of hydrated silica as eq. 3, 4 and 5 or formation of fluorides by reacting with sodium as sodium silicates, potassium into potassium silicates, and calcium into calcium fluoride; as given in eq. 9, 7 and 8.

These reactions occur in multiple stages and are highly sensitive to temperature and pressure, making job execution challenging. Estimating the extent of formation damage caused by these precipitates is difficult due to reservoir heterogeneity and variations in mineral composition. Thus, selecting and designing the right stimulation fluid is crucial, as different formulations may offer specific advantages depending on the reservoir conditions.

One significant challenge is the rapid increase in HF reaction rates at temperatures above 200 °F, leading to excessive early acid consumption and reduced efficiency. To counter this, researchers have explored alternative acids such as fluoroboric acid (H_8F_4) and phosphoric acid (H_3PO_4), which are less corrosive and more stable under high temperature [23].

During job execution, pre-flush and over-flush treatments with ammonium salts help remove incompatible ions (Na^+, K^+, and Ca^{2+}) that could form insoluble fluorosilicates (e.g., Na_2SiF_6). To prevent excessive near-wellbore deconsolidation, the maximum HF concentration is typically limited to 3%. The HCl/HF ratio generally ranges between 4:1 and 9:1 [13]. Additionally, prolonged well shut-ins can lead to re-precipitation of reaction products, causing secondary formation damage. This issue arises when HF first reacts with aluminosilicates to form fluorosilicates, which further react with clays to form insoluble sodium and potassium fluorosilicates. Prevention strategies include:

- Over-flushing with dilute HCl or NH_4Cl to push reaction products deeper into the formation.
- Using delayed acid formulations that gradually release HF. Employing buffered acid systems to allow deeper acid penetration before significant reaction occurs.

Precipitates such as CaF_2 and AlF_3 in spent acid solutions also contribute to potential damage. Based on these challenges, researchers have proposed new acid formulations to minimize precipitation under high-temperature conditions. Ongoing experimentation is crucial to developing more effective acid combinations tailored to specific reservoir properties and conditions.

Conclusions

1. The stimulation of sandstone reservoirs remains a complex challenge due to their inherent heterogeneity, making it difficult to apply a single universal method. A thorough understanding of the mineralogy and cement composition of sandstone is essential for designing an effective stimulation treatment. Although quartz is dominant mineral in sandstone but feldspars, lithic fragments, micas, clay minerals and cement like quart, siderite, carbonate are responsible to make job difficult. Neglecting factors such as iron content in the rock cement or matrix can result in severe formation damage, underscoring the importance of careful job planning.
2. Mud acid, commonly formulated with a hydrofluoric acid (HF) to hydrochloric acid (HCl) ratio of 3 : 12, has proven effective in minimizing additional formation damage when combined with ammonium chloride and iron control agents. The variability in HF : HCl ratios allows for tailored formulations, ensuring optimal reaction with silica while controlling unwanted precipitation. However, under high-temperature conditions, additional acid combinations are often required to prevent precipitation-related complications.
3. Overall, the effectiveness of sandstone stimulation relies on a detailed understanding of rock composition and the strategic selection of acidizing fluids to maximize permeability enhancement while minimizing formation damage.

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