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Electrokinetic Driven Low-Concentration Acid Improved Oil Recovery in Abu Dhabi Tight Carbonate Reservoirs

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A B S T R A C T

Conventional acidizing, though useful in increasing the effective permeability in the near well-bore region, has compatibility and operational issues such as limitation in depth of penetration and HSE issues to handle, transport and injection of high concentration acid into the well. However, the application of electrokinetics (EK) has a number of economic and environmental advantages such as reduced oil viscosity, reduced water-cut, and no depth limitation. This study presents recent research that demonstrates the impact of EK on matrix low-concentration acid stimulation in Abu Dhabi carbonate reservoirs with varying acid concentrations and voltage gradients.

Core-flood tests were conducted by saturating core-plugs retrieved from Abu Dhabi oilfields with medium and light crude oil in a specially designed HPHT EK-EOR core-flood setup. Initially, EK was applied using acids of varying concentrations from 0.125 to 1.2% HCl injected at the anode to cathode (producer) at 0.25ml/min. Experiments were also repeated with low concentration HCl stimulation without the application of EK.

Several correlations related to acid concentration, displacement efficiency and permeability enhancement are presented here at ambient and reservoir conditions. The experimental results have shown that the application of waterflooding on the carbonate cores yields an average oil recovery of 60%. An additional 17-29% oil recovery was enhanced by the application of EK-assisted low concentration (~2%) HCl at Abu Dhabi reservoir conditions. In addition, EK LCA-IOR was shown to enhance the reservoir's permeability by approximately 11-53% across the tested core-plugs. Furthermore, this technique can be engineered to be a sustainable process in the presence of EK as the concentration and voltage gradient can be optimized to reduce the amount of acid injected and power consumption by 20-41%, further improving economic feasibility.

1. Introduction

A large fraction of original oil in place is left behind in the reservoir after primary recovery phase. Secondary (pressure maintenance) and tertiary (pressure maintenance along with playing with physiochemical properties of rock-fluid) phases are practiced to recover as much as possible from the remaining oil based on economic and environmental approaches [1]. Even after application of the current methods, oil recovery is not that as expected due to a global increase in oil demand by 35% from 2008-2035 with an increase in world marketed energy consumption increase by 53% [2]. IOR (Improved Oil Recovery) is used to describe any process, or combination of processes, that may be applied to economically increase the cumulative volume of recoverable oil from the reservoir at an accelerated rate. IOR may also include EOR (Enhanced Oil Recovery) processes which are used to mobilize and recover that percentage of residual oil that cannot be captured by waterflooding alone, or by the use of physical, mechanical, or procedural processes [3]. EOR technologies are specifically designed to affect mostly the immobile oil that remains in the reservoir, while IOR strategies can be used to recover more of the remaining mobile oil and/or immobile oil [4–5]. IOR (Improved Oil Recovery) has been at the forefront of oil and gas R&D for the past 4 decades as it helps in the improvement of the hydrocarbon sweep efficiency by causing an increase in recovery factor and a reduction in residual oil saturation.

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Nomenclature

ADNOC	Abu Dhabi National Oil Company
CONV	Conventional
DC	Direct Current
DE	Displacement efficiency
EK-EOR	Electrokinetic Electrically Enhanced Oil Recovery
Fig. /Figs.	Figure / Figures
HCl	Hydrochloric acid
HPHTHS	High Pressure High Temperature High Salinity
IOR	Improved oil recovery
J	Current Density
K_{enh}	Permeability enhancement
LCA	Low-concentration acid
PV	Pore Volume
PI-EKRC	Petroleum Institute – Electrokinetics Research Center
R&D	Research and Development
SEQ / SIM	Sequential / Simultaneous
V/cm	Volt per / centimeter
WF	Waterflooding

This research focuses on analyzing the effectiveness of the EK LCA-IOR process that allows us to shift from conventional to simultaneous LCA-IOR. In order to guide the acid through the tortuous path, an optimum acid concentration and voltage gradient is identified that reduces the amount of acid concentration and volume required by preventing acid from getting adsorbed too early on the rock surface, resulting in enhanced depth of penetration and increased oil displacement efficiency.

1.1. Conventional Low-concentration acidizing

During various workover operations, liquids from muds penetrate into the reservoir rock that fills the pore spaces and blocks the pore throats resulting in the formation of an impermeable layer or more commonly known as skin [6]. In addition to this, sometimes formations with very low petrophysical properties provide insufficient productivity even if the skin damage is not considered. Therefore, good stimulation techniques should be used in order to increase well productivity by removing the greater part of the skin along the full extent of the wellbore or to increase the low permeability of the rock in order to enhance the depth of penetration while increasing the recovery factor as well. Matrix acidizing (with acid concentration of up to 15%) commonly enhances production by increasing the effective wellbore radius and causing stimulation as seen in earlier large scale studies [7]. Matrix acidizing experiments combined with visualization techniques are commonly used to study the details of wormhole networks formed during matrix acidizing of carbonates [8]. Several treatment parameters such as acid injection rate, acid concentration, and variation of rock permeability, reservoir temperature and acid volume injected are optimized to execute an efficient acidizing job in carbonate reservoirs [9–10]. Experimental acid injection rates are selected to achieve the desired acid flux at a specified radial distance from the wellbore with a single dominant wormhole formed that penetrates the entire length of the core. However, the optimum rate is found to be a function of the rock composition and reaction temperature as well as the pore size distribution of the formation rock [11]. HCl (Hydrochloric acid) is used for acidizing and stimulating carbonate reservoirs at a large scale. The following factors control the acid reaction rate with the carbonate reservoirs [12–13]:

1. Area of contact per unit volume of acid
2. Formation temperature and pressure
3. Acid Viscosity
4. Acid (HCl) concentration
5. Acid type and physical and chemical properties of formation rock
6. Flow velocity of acid

1.1.1. Low-concentration acidizing limitations

Acidizing jobs have been effective in stimulating wells due to an increase in the effective permeability of the formation. However, the lack of precision in completing the job in a timely manner has the following operational constraints including environmental and financial costs [14–16]:

- Acidizing has a limited depth of penetration near wellbore as it does not stimulate deep into the formation due to the rapid reaction rate between HCl and carbonate as it is controlled by the following factors [12]:
  - acid fluid loss
  - reaction rate
  - fracture flow rate
- High concentration of injected acid creates HSE issues as it is a hazard to handle, transport and inject into the well due to its high corrosivity, rapidly affecting well tubulars.
- High consumption costs occur during injection of chemicals due to losses by adsorption/absorption with a low depth of penetration and therefore, it may not be economically feasible.

1.2. Electrokinetics-Enhanced Oil recovery

Electrokinetics is the application of direct current (DC) using electrodes (anode and cathode) to employ EK phenomena in reservoir fluids resulting from the differential movement of ions across the electrical double layer (EDL) [17–18]. This technology has been proven in laboratories for the past 6 decades, where oil mobilization due to application of DC was first attempted in the 1960's by Chilingar and his associates at the University of Southern California [19–20]. To a limited extent the technology has been proven in the field, with reported advantages such as no depth limitation, reduced water-cut, reduced fluid viscosity and reduced H_2S production. Five mechanisms appear to influence EK-EOR including Joule heating, electromigration, electrophoresis, electroosmosis and electrochemically enhanced reactions. All of these mechanisms are collectively called electrokinetics and contribute to oil mobility and permeability enhancement [19,21–26].

1.3. EK Low-Concentration Acid IOR (EK LCA-IOR)

Acid injection along with the application of Electrokinetics is an emerging technology which results in yielding higher reserves with a greater enhancement in permeability in lab scales [27]. EK Low-concentration acidizing IOR (EK LCA-IOR) hypothesis is developed that drives the acid deeper into the reservoir and reduces the adsorption capacity on the reservoir rock surface along with the following additional merits [28–29]:

- Enlarges displacement efficiency and reduces oil viscosity
  - Reduces Interfacial tension, alters wettability and enhances capillary number
  - Targets un-swept (residual) oil driven by electric field through electrophoresis and electroosmosis.
- Enhances penetration depth along with permeability enhancement particularly in moderate to tight zones