EVALUATION OF NANO SILICA FLUID RECOVERY MECHANISMS FOR ENHANCED OIL RECOVERY

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ABSTRACT

This study aims to evaluate the oil recovery potential of hydrophilic silica nanofluids in sandstone reservoirs at varying salinities and concentrations. The impact of nanofluid as secondary and tertiary recovery mechanisms on recovery potential is also discussed, and recovery mechanisms are determined for all flooding parameter variations. The integrated study of parameters, recovery, and mechanism is to outline the impact of changes in fluid parameters on mechanisms and recovery for future clear understanding of the mechanisms at a specific set of nanofluid conditions. The study conducted at ambient conditions and flooding was carried out at 1000 psi overburden pressure. The nano flooding was carried out for 12 nano meter nanosilica with concentrations of 0.02 wt. %, 0.05 wt. %, 0.07 wt. % and 0.10 wt. % in salinity ranges from 20,000 to 40,000 ppm. Along with recovery potential, recovery mechanisms were also determined by contact angle evaluation, interfacial tension (IFT) measurements, porosity reduction evaluation, and pressure differential monitoring. In scenario 1, it was observed that the highest recovery at 20,000 ppm salinity was achieved with 0.05 wt. % of nanosilica which was approximately 11% of original oil in place (OOIP). The dominant mechanism was found to be wettability change to water wet condition (i.e., reduced to 46º) and interfacial reduction (i.e., reduced to 14.9 from 18.5 mN/m), whereas for higher concentrations mechanical mechanisms like mechanical entrapment along with pore jamming were also found to play the role. Whereas in scenario 2, where salinities were changed, the highest recoveries were recorded for 20,000 and 40,000 ppm (i.e., 11% and 11.2% of OOIP respectively). In the case of 20,000 ppm salinity, wettability change and IFT reduction played the dominant role but when salinity was increased to 30,000 ppm, due to instability of the solution the impact of wettability change and IFT reduction subsided hence recovery declined to 8.33% of OOIP. In the case of 40,000 ppm though nanofluids formed agglomerations and wettability change and IFT reduction were not dominant but mechanical entrapment enhanced the recoveries further. In the third scenario, it was outlined that at lower injection rate of 0.5 ml/min the recovery potential was lowered, as reduction in disjoining and mechanical mechanisms impact was observed. Application of nanofluids as tertiary recovery mechanism was found to be suitable as compared to secondary recovery in terms of recovery. Hence for optimum effect of nano flooding on oil recovery, the optimum design of nanofluid concentration, stability, injection rate, and mode of application have been identified. For the most effective nano flooding it should be ensured that major mechanisms like wettability change, interfacial reduction, and log jamming remain equally active. The study establishes that design of any nano flooding as tertiary recovery mechanism would be effective when a mechanistic study is carried out ensuring effectiveness of chemical and mechanical mechanisms which would result in incremental recovery.

ABSTRAK

Tujuan kajian ini adalah untuk menilai potensi perolehan minyak menggunakan nanobendalir silika hidrofilik bagi reservoir batu pasir pada kemasinan dan kepekatan nanosilika yang berbeza. Kesan nanobendalir sebagai mekanisme perolehan sekunder dan tertier terhadap potensi perolehan turut dibincang, dengan mekanisme perolehan ditentukan untuk semua perubahan parameter banjiran. Kajian bersepadu bagi parameter, perolehan, dan mekanisme adalah untuk merangka impak terhadap perubahan parameter bendalir pada mekanisme dan perolehan bagi pemahaman tentang mekanisme yang lebih jelas pada keadaan tertentu nanobendalir. Kajian ini dilakukan pada keadaan ambien dengan banjiran dilaksanakan pada tekanan beban atas 1000 psi. Banjiran nano dilaksana menggunakan nanosilika bersaiz 12 nano meter dengan kepekatan 0.02 % berat, 0.05 % berat, 0.07 % berat, dan 0.10 % berat pada kemasinan berjulat dari 20,000 ppm sehingga 40,000 ppm. Seiring dengan potensi perolehan, mekanisme perolehan juga ditentukan menerusi penilaian sudut sentuh, pengukuran, tegangan antara muka (IFT), penilaian pengurangan keliangan, pemantauan tekanan kebezaan. Pada senario 1, didapati perolehan tertinggi adalah lebih kerrang 11 % daripada minyak asal di tempat (OOIP) pada kemasinan 20,000 ppm yang dicapai dengan 0.05 % berat nanosilika. Mekanisme utama adalah perubahan keterbasahan kepada keadaan basah air (berkurang kepada 46^{o}) dan pengurangan tegangan antara muka (iaitu berkurang menjadi dari 18.5 ke 14.9 mN/m). Bagi kepekatan nanosilika yang lebih tinggi mekanisme mekanikal seperti pemerangkapan mekanikal berserta dengan penyesakan liang turut berperanan. Sebaliknya bagi senario 2, dengan kemasinan diubah, perolehan tertinggi direkodkan pada 20,000 dan 40,000 ppm (iaitu masing-masing 11% dan 11.2% daripada OOIP). Bagi kemasinan 20,000 ppm, perubahan keterbasahan dan pengurangan IFT memainkan peranan yang dominan, tetapi apabila kemasinan ditingkatkan kepada 30000 ppm, oleh sebab berlakunya ketakstabilan larutan, maka impak perubahan keterbasahan dan pengurangan IFT terjadi melemah yang menyebabkan penurunan perolehan kepada 8.33% daripada OOIP. Bagi kemasinan 40,000 ppm, walaupun nanobendalir membentuk gumpalan dengan perubahan keterbasahan dan pengurangan IFT adalah tidak dominan tetapi pemerangkapan mekanikal boleh meningkatkan perolehan. Bagi senario ketiga, didapati bahawa pada kadar suntikan yang lebih rendah iaitu pada 0.5 ml/min telah menghasilkan potensi perolehan yang rendah berikutan berlakunya pengurangan impak mekanisme tak searas dan mekanikal. Pengaplikasian nanobendalir mekanisme perolehan tertiar adalah lebih sesuai berbanding perolehan sekunder dari segi perolehan. Oleh itu bagi mengoptimumkan kesan banjiran nano terhadap perolehan minyak, reka bentuk optimum bagi kepekatan nanobendalir, kestabilan, kadar suntikan dan mod pengaplikasian telah dikenal pasti. Banjiran nano yang paling berkesan perlu memastikan mekanisme utama, misalnya perubahan keterbasahan, pengurangan tegangan antara muka dan penyesakan log semuanya aktif berperanan secara seimbang. Kajian ini mengesahkan bahawa reka bentuk sebarang banjiran nano sebagai mekanisme perolehan tertier akan menjadi berkesan apabila sesuatu kajian mekanistik dilaksana bagi memastikan keberkesanan mekanisme kimia dan mekanikal, yang mampu menghasilkan perubahan tokokan.

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LIST OF ABBREVIATIONS

OOIP	-	Original oil in place
EOR	-	Enhanced oil recovery
CEOR	-	Chemical enhanced oil recovery
IFT	-	Interfacial tension
SiO_2	-	Silicon dioxide
Wt. %	-	Weight %
CSS	-	Cyclic steam simulation
SAGD	-	Steam assisted gravity drainage
N_2	-	Nitrogen
CO_2	-	Carbon dioxide
WAG	-	Water alternating gas
SWAG	-	Simultaneous water alternating gas
FAWAG	-	Foam assisted water alternating gas
NPs	-	Nanoparticles
TiO_2	-	Titanium dioxide
Al_2O_3	-	Aluminium oxide
SDS	-	Sodium Dodecyl Sulphate
Ppm	-	Particles per million
Nm	-	Nano meter
RF	-	Recovery factor
PSD	-	Particle size distribution
ZP	-	Zeta Potential
PV	-	Pore Volume
WF	-	Water flooding

LIST OF SYMBOLS

I_w	-	Wettability Index
V_o	-	Volume of oil
V_w	-	Volume of water
S_{wr}	-	Residual water Saturation
S_{or}	_	Residual Oil Saturation
K_{ro}	-	Oil Relative permeability
M	-	Mobility Ratio
λ_i	-	Injected fluid mobility
λ_o	-	Oil mobility
K_{ri}	-	Relative injected fluid permeability
C_{NP}	-	Concentration of nanoparticle
C_{opt}	-	Optimum concentration
d_H	-	Hydrodynamic diameter
μ	-	Viscosity
D	-	Translational diffusion constant
ED	-	Displacement efficiency

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The world's energy needs have risen because of rapid industrialization in the contemporary era. While renewable energies have recently been suggested, the key contributors to energy supply remain the traditional non-renewable energy sources, with hydrocarbons being the most heavily relied on. The oil fields throughout major oil-producing regions are nearing the end of their useful life. The vast mature fields are on the verge of being abandoned, with almost half of the original oil in place (OOIP) left unrecovered [1,2]. As mature fields deplete and higher capital costs halt new projects, professionals' emphasis has turned to enhance the ultimate recoveries of developed fields to meet the needs of the market. Enhanced oil recovery (EOR), also known as tertiary recovery, is a process that aids in recovery increment by enhancing recovery (by altering the fluid-fluid and fluid-rock interactions inside the reservoir). Existing EOR methods can recover 30-60% or more of the hydrocarbons, compared to 20-40% recovered by primary and secondary recovery methods [3]. The most advanced approach used is chemical enhanced oil recovery mechanisms (CEOR), in which various additives, polymers, surfactants, emulsions, or variants of more than one is used as displacing fluid to change microscopic properties as well as an additional macroscopic influence of simple flooding and improve recoveries.

Even after the incorporation of these complicated techniques, oil remains trapped, however, the use of nanoparticles in EOR as nanofluid has opened new frontiers for improving recoveries to new limits. Nano based EOR allows modifications of the properties of displacing fluid at the nanoscale consequently microscopic recovery enhancing parameters are optimized. Promising results found at the lab scale have contributed to shifting focus to nanofluids. Nanofluids have been found to enhance recoveries in sandstone and carbonate reservoirs at the lab scale [4,5,6]. The detailed investigation concludes that as the EOR additives have been replaced with nano particles in displacing fluid, their impact is higher compared to previously used CEOR additives, as the major increment in recovery is contributed by the smaller pores that were not impacted previously. Owing to their hydrophilic attribute of dispersing in the water phase, they enhance recoveries by changing the wettability of the system to water wet. The shift of wettability to water wet sets free trapped reservoir fluid ultimately enhancing recovery further. The smaller size of these particles (nanomaterials) sticks around the rock pore surface which enhances recovery by disjoining mechanism. The smaller the size of the nanomaterial more is the impact due to this disjoining impact of the nanofluids. They also serve as viscosity enhancers and improve recovery by improving mobility. Other mechanisms like the log jamming effect, clogging at pore throat and IFT reduction all play an important role in contributing to incremental recovery [7]. Hence the success of any nanomaterial application in the system depends on what mechanisms amongst them are dominant and to what extent.

Nanofluids despite being an efficient agent to enhance recoveries have rarely been evaluated in pilot or field tests. The reasons for this slow process are more than one and a few amongst them are economics, environmental constraints in few countries, and contradiction of recovery output results [8]. Irreproducibility of recovery results is due to many uncertainties such as the lack of detailed evaluation studies of rock properties, and concentrations, retention ability, and stability of nanofluids that have not been integrated to achieve the optimum setting of these parameters. Even though it has been established that the nanofluids are comparatively feasible than many current CEOR methods however above-mentioned hurdles have delayed utilizing the true potential of nanomaterials in the field of EOR.

Many metallic and non-metallic NPs have been utilized at lab scales but amongst them, silica NPs are considered as the most suitable nanomaterial to be implied in sandstone cores because of their technical, environmental, and economical advantages [9,10]. Due to their hydrophilic attribute, they tend to change wettability from oil-wet to water-wet and reduce the interfacial tensions [11]. The interfacial reduction has also been reported to be amongst the effective mechanism. All these mechanisms are impacted by various factors such as particle concentration, particle size, injection rate, salinity, and stability of the nanofluid.

Many studies have been published that have worked on stabilising the nano-based fluids for enhanced oil recovery applications whereas identification of mechanisms for any instability that may occur have not been outlined. The understanding of mechanisms without use of any stabilisers can be helpful in designing optimal nano-based recovery fluids which may be effective even if harsher environments are encountered. Evaluation of nano particles on range of salinities and with different concentration will cause expected instabilities hence their impact on recovery and understanding of underlying mechanisms can be beneficial for future research and applications of nanofluids as EOR agents.

1.2 Problem Statement

Integration of nanoparticle in general and SiO_2 NPs in specific, in EOR techniques has given optimistic results on a lab scale. Despite promising results, pilot and field applications have not taken place and the reason for that is on technical, environmental, and economical aspects of nano-EOR methods. The major focus of the research at the lab scale to date has been around higher recovery using SiO_2 nanoparticles, but optimal conditions are yet not outlined. The optimum conditions in which still not established due to contradiction in results [12], stability being important is hard to establish, lack of integrated study for understanding mechanisms [13], and factors affecting recovery potential. All the studies carried out have independently investigated wettability alteration, IFT reduction, colloidal stability, and the impact of varying concentrations on recovery enhancement. But most of the work carried out has not been able to establish the fact about major contributing mechanisms in recovery enhancement by the nanofluid application. The theoretical understanding states that with increasing concentration, recoveries should also increase but most of the lab work carried on has shown that recoveries at higher concentrations have been lesser than those at lower concentrations. Despite high recovery potential in most of the studies at lab scale, the challenges associated with applicability are due to:

- Recovery enhancement results by silica nanofluids have contradicted to be high and low in different lab studies, as in at one stance it was 14.29 % [51],while in another study, it was found to be 2% OOIP only as reported by Hu et al [14].

- Concentration being an important criterion requires the identification of an optimized nanoparticle concentration to be identified for application in sandstone reservoirs. Each reported study has identified different concentration as optimum in recovery enhancement, normally in ranges of 0.01-0.10 wt. %.

- Recovery mechanisms attributed to silica nanofluid recovery enhancement have not been clearly outlined and major contributing mechanisms have differed in different studies. Wettability changes, interfacial tension reduction, pore throat plugging, and mechanical entrapment of particles are the commonly reported mechanisms when nanofluids are implied.

- Stability remains a challenge in the application of nanofluids in highly saline environments. Despite achieving stability in many lab-based studies, the unpredictability of harsher scenarios requires understanding of mechanisms even if solutions become unstable to certain degrees.

1.3 Research Objectives

This study majorly focuses on the evaluation of work that has been carried out regarding nano particle based EOR with the focus on recoveries, the concentration of nanomaterial, and stability in a high saline environment. Since most reported lab work has resulted in better recoveries and is among the most environmentally acceptable due to silica content, silica nanoparticles were chosen for evaluation in sandstone reservoirs. Though stability without stabilizers is expected to be compromised this study aims to evaluate silica nanofluids without stabilizing the solution, as the use of stabilizers may cross the economical limits. Hence the true objective of our study is to evaluate various parameters that affect the recovery potential of silica nanofluids and the changes in mechanisms associated. Though progress has been made on several fronts independently in the past, no integrated methodology has been used to build confidence in results and ensure that the same results can be replicated under similar conditions. Thus, the objectives of this research are:

I. To assess the impact of salinity on the oil recovery potential of hydrophilic Silica (SiO_2) nano particles from low to high salinities (i.e. 20000, 30000, and 40000 ppm) at variable concentrations of 0.02, 0.05, 0.07 and 0.10 wt. %.

II. To evaluate the impact of injection rate at variable injection rates (1.0 ml/min and 0.5 ml/min) and mode of application on oil recovery potential of silica NPs as tertiary and secondary recovery mechanisms.

III. To determine the impact of recovery mechanisms of wettability alteration, interfacial tension (IFT) reduction, material retention and pore plugging due to variance in material design parameters.

1.4 Scope of the Study

The performance of nanofluids in recovery enhancement has been reported to be based on their concentration, particle size, nanoparticle stability in solutions, reservoir environment, wettability alteration ability, and suitability to the type of reservoir. Whereas studies have reported different recovery mechanisms as the contributing phenomenon in the recovery output due to application of silica based nano particles. Hence scope of this study is limited to:

a) Evaluating the recovery potential of silica nano particles as enhanced oil recovery technique in nano particles concentration of 0.02, 0.05, 0.07 and 0.10 wt. %, as beyond 0.10 wt. % the effectiveness of nano particles reduces due to larger agglomerations.

b) The nano fluids would be prepared using brine as the base solution using sodium chloride (NaCl) for salinity of 20000-40000 ppm.

c) Flooding is carried out for different injection rates i.e. 0.05 ml/min and 0.10 ml/min, whereas secondary and tertiary recovery mechanisms are evaluated to evaluate the effective in each mode of application.

d) For recovery mechanisms evaluation wettability changes, interfacial tension IFT, retention, and pressure differential evaluations are carried out to establish relationship between mechanisms and parameters like concentration, salinity, injection rates and mode of application.

e) Four Castlegate cores and three Berea sandstone cores have been utilized in core flooding experiments conducted with average porosities of 20-25 % and average permeability of 400-600 mD.

1.5 Significance of the Study

As the conventional reservoirs are depleting and lower crude oil prices have halted the execution of the new ventures, it has become eminent that current producing fields produce maximum recovery. Advent of novel methods has enhanced recovery potentials at field and lab scale by utilizing advanced methodologies. The application of nanotechnology in EOR mechanisms has been successful in lab studies. Nano particle induced EOR is the field that can cater to the energy needs of the world. This study aims to find out optimum concentration at which we achieve better recoveries are achieved and underlying mechanisms are identified with changes in concentrations and salinities. Generally, this study intends to enhance understanding regarding mechanistic impact of NPs at variable parameters with changes in stability, hence clear understanding of mechanism shall help in designing nano-based recovery applications that would help in enhancing recovery potential of the fields. This study enhances the understanding regarding mechanistic changes at variable parameters which can impact the design of silica based nano fluids as an EOR technique.

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