NUMERICAL SIMULATION ON FOAM STABILITY AND ELECTROKINETIC POTENTIAL DURING FOAM INJECTION

AMNI HASLINDA BINTI ALPANDI

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School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

This thesis is dedicated to my parents, family, teammates and all the beloved ummah.

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In the name of Allah, The Beneficent, The Merciful.

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ABSTRACT

Numerical models in petroleum reservoir simulation are valuable tools to visualize the pattern of reservoir fluid flow and to estimate production oil. Modelling enhanced oil recovery (EOR) processes requires a complex mathematical model to integrate multiphase flow and electrokinetic phenomena. There have been limited studies done in combining foam stability and electrokinetics by using simulation tools. This study aims to build and integrate a numerical model of foam progression and electrokinetic behaviour in foam injection process. This model was built using COMSOL Multiphysics 5.3 software to investigate fluid flow profiles in free liquid films stabilised by anionic surfactant, simulate foam progression and electrokinetic measurement with reasonable accuracy. Validation of the numerical model was done using finite element method. Several recent lab and simulation works were compared with this numerical simulation result to fill the gap in this research area. Hence, the relationship between stability of foam and the associated streaming potential signals was obtained. The finding shows that the algorithms suitable for this foam injection case are continuity equation, conservation of species transport, Navier Stokes equations and electric current conservation. Based on the comparison, this simulation study has high level of similarity with previous experimental and simulation works. Therefore, the effectiveness of the EOR in terms of foam stability can be monitored in real time.

ABSTRAK

Model berangka dalam penyelakuan reservoir petroleum ialah satu alat yang berharga bagi mencerap corak aliran bendalir reservoir dan menganggar pengeluaran minyak. Pemodelan proses perolehan minyak tertingkat (EOR) memerlukan model matematik yang kompleks bagi menyepadukan aliran berbilang fasa dan fenomena elektrokinetik. Tidak banyak kajian yang dilakukan dalam menggabungkan kestabilan busa dan elektrokinetik menggunakan alat penyelakuan. Kajian ini bertujuan untuk membina dan menyepadukan model berangka pergerakan busa dan tingkah laku elektrokinetik dalam proses suntikan busa. Model ini dibina menggunakan perisian COMSOL Multiphysics 5.3 yang boleh mengkaji profil aliran bendalir dalam filem cecair bebas yang disokong oleh surfaktan anionik, menyelaku pergerakan busa dan pengukuran elektrokinetik dengan ketepatan yang munasabah. Pengesahan model berangka dilaksana menggunakan kaedah elemen finite. Beberapa kerja makmal dan penyelakuan terkini dibandingkan dengan hasil penyelakuan berangka ini bagi memenuhi jurang dalam bidang penyelidikan terbabit. Oleh itu, hubungan antara kestabilan busa dengan isyarat potensi aliran yang berkaitan berjaya diperoleh. Dapatan menunjukkan bahawa algoritma yang sesuai untuk kes suntikan busa ialah persamaan selanjar, pemuliharaan pengangkutan spesies, persamaan Navier Stokes dan pemuliharaan arus elektrik. Berdasarkan perbandingan, kajian penyelakuan ini mempunyai tahap kesamaan yang tinggi terhadap hasil uji kaji dan penyelakuan sebelumnya. Oleh itu, keberkesanan EOR dalam bentuk kestabilan busa boleh dipantau dalam masa nyata.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
ALE	-	Lagrangian Eulerian Algorithm
CFD	-	Computational Fluid Dynamic
CMC	-	Critical Micelle Concentration
CPU	-	Central Processing Unit
DC	-	Direct Current
DOFs	-	Degrees of Freedom
EDL	-	Electric Double Layer
EHD	-	Electrohydrodynamics
EKSF	-	Electrokinetic Soil Flushing
EOR	-	Enhanced Oil Recovery
FAWAG	-	Foam Assisted Water Alternating Gas
FD	-	Finite Difference
FEM	-	Finite Element Method
GIT	-	Grid Independence Test
GOR	-	Gas Oil Ratio
IFT	-	Interfacial Tension
LBM	-	Lattice Boltzmann Method
MEMS	-	Microelectromechanical system
NS	-	Navier Stokes
PDEs	-	Partial Differential Equations
PNM	-	Pore Network Model
PNP	-	Poisson Nernst Planck
SAG	-	Surfactant Alternating Gas
SDS	-	Sodium Dodecyl Sulphate
VSP	-	Vertical Seismic Profiling
WAG	-	Water Alternating Gas

LIST OF SYMBOLS

β_0	-	Zeta Potential at the Surface Covered Solid-Liquid Interface
C_i	-	Concentration
cm	-	Centimetre
CO_2	-	Carbon Dioxide
Cu/CuCl	-	Copper/Copper Chloride
D	-	Diameter
D_i	-	Diffusion Coefficient
E	-	Electric Field
ϵ_0	-	Absolute Permittivity of Vacuum
ϵ_r	-	Relative Permittivity of the Test Fluid
$\epsilon_r\epsilon_0$	-	Solution Permittivity
f	-	Foam Quality
F_{ivf}	-	Force Per Unit Volume
h , hr	-	Hour
H^+	-	Hydrogen Ion
I	-	Identity Matrix
L	-	Length
min	-	Minutes
mm	-	Millimetre
mV	-	MilliVolt
NaCl	-	Sodium Chloride
η	-	Dynamic Viscosity
OH^-	-	Hydroxide Ion
p	-	Pressure
ppm	-	Part Per Million
Φ	-	Electric Potential
R_i	-	All the Reactions Involving Species i
s	-	Seconds
u	-	Velocity Field Vector

$u_{G/L}$	-	Slip Velocities Gas-Liquid
μ_i	-	Mobility
μm	-	Micrometre
$u_{S/L}$	-	Slip Velocities Solid-Liquid
V	-	Electric Potential
V_g	-	Volume of Gas in Foam
V_l	-	Volume of Liquid in Foam
ψ_0	-	Zeta Potential at the Surfactant Covered Gas-Liquid Interface
z_i	-	Electric Charge

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

In 1958, foam injection was first introduced as an enhanced oil recovery (EOR) method and foam was able to act as an agent for gas blocking. In EOR process, foam has shown favourable characteristics of flow including mobility, flow diversion to region of low permeability and selective blocking of thief zones (Farajzadeh *et al.,* 2012).

A dispersion of gas in a continuous liquid phase is known as foam. However, the gas phase is discontinuously organized in gas bubbles. Besides that, with the presence of surfactant, flowing gas in porous medium causes the generation of foam (Simjoo *et al.,* 2012). The surfactant solution in a liquid phase acts as a stabilizer when the gas breaks into bubbles.

After a period of hydrocarbon production, pressure in the reservoir will be depleted and this situation might lead to the use of EOR as a solution (Tunio and Chandio, 2012). Foam Assisted Water Alternating Gas (FAWAG) has been applied as one of the EOR techniques because of the capability to maximize the rate of hydrocarbon production in the production tubing, reduce gas oil ratio and improve sweep efficiency especially during gas injection. Moreover, FAWAG also becomes a new method for the improvement of well flow. By delaying early gas breakthrough, FAWAG provides better control of mobility for gas flow (Shabib-asl *et al.,* 2014).

Several researchers have proposed to use electrical current for EOR. In producing reservoir, passing of electrical current between electrodes is a process in electrical enhanced oil recovery. Alternating current (AC) electricity has been proposed in order to heat oil recovery which causes decreasing viscosity of oil and enhanced recovery (Wittle, Hill and Chilingar, 2011). Unfortunately, AC current face some problems such as corrosion of electrodes, losses of inductive energy and shallow penetration missing from the electrodes. In the application of direct current (DC) EOR, these problems do not occur. Wittle *et al.* (2011) suggested to use DC current with high density to drive oil into wells from reservoirs.

When tangential electric field interrelates with a charged surface immersed in electrolyte solution, a phenomena called electrokinetic has been discovered. When a liquid is forced through the system, the movement of part of the Electric Double Layer (EDL) from the charged pore surfaces is defined as the effects in a porous system by the electrokinetic. The movement of liquid through capillaries brings a net charge which is a mobile part known as EDL and this causes the increase of the streaming current. The potential at the shear surface between the charged surface and the electrolyte solution is one of the factors affecting the electrokinetic behaviour. This potential is known as zeta potential or electrokinetic (Omar *et al.,* 2013).

A thin charged double layer exists in reservoir rocks at the interface between the water in the pores and the rock matrix. Usually, the matrix surface is negatively charged. Electric current is produced when the water moves under a pressure gradient. Omar *et al.* (2013) stated that the source of the streaming potential is this conductive current. By providing direct information on the charged solid and the liquid interface, electrokinetic technique becomes a valuable tool for monitoring processes in EOR applications.

In order to control mobility ratio and improve the volumetric sweep efficiency, foam is widely used in EOR displacement process. Stability of the foam film is a factor that affects the process efficiency of foam displacement. However, this direct observation of foam stability in laboratory using physical observation is not possible to be applied in reservoir. Therefore, Omar *et al.* (2013) proposed a better alternative which is using the electrokinetic potential to measure indirect assessment of foam stability. Previously, a detecting tool for the encroachment of water towards a production well has been recommended using the measurement of electrokinetic potential (Jackson, 2010). By installing the electrodes downhole, the dynamics of electrically charged fluid in porous media such as the formation and injected fluid can be measured (Mohd *et al.,* 2017).

1.2 Statement of Problem

Mathematical models in petroleum reservoir simulation are valuable tools in order to visualize the pattern of reservoir fluid flow and to estimate the production of oil. Electrokinetic study in the EOR requires a complex mathematical modelling to integrate multiphase flow and process of the electrokinetic transport.

Recent laboratory experiment by Omar (2017) has been conducted to investigate the relationship between foam stability and electrokinetic phenomena. However, the experimental result has not been validated by any numerical modelling. In terms of modelling, many studies have looked at the progression of foam in reservoirs and a few numerical studies also have been conducted to predict electrokinetic potential variation in the water flooding process. Nevertheless, there are limited studies that combine foam stability and electrokinetic in the reservoir. Therefore, a recent laboratory and few simulation works were compared with this simulation work to fill the gap in this research area.

Moreover, most of the previous experiments and simulations conducted by other researchers related to electrokinetic phenomena during foam system involved an electro-osmosis process. However, there are limited studies that combine foam stability and streaming potential signal. Therefore, this simulation study focuses on streaming potential to fill the gap in this research area.

1.3 Objectives of Study

Followings are the objectives proposed for this study:

(a) To develop a numerical models for foam progression and electrokinetic behaviour in foam injection process.

(b) To validate the numerical model by using Finite Element Method (FEM).

(c) To compare simulation result with previous experimental work in relation to foam stability and associated streaming signals in foam injection process.

1.4 Scopes of Study

The study area of this research is focusing on the fundamental of governing equation of electrokinetic EOR, mass transport model of electrokinetic, coupling of electrical and pressure gradients, the solution strategy used and the implementation of numerical model for the simulation process. In addition, governing equation of fluid dynamic such as foam, modelling of the multiphase flow in porous media, fundamental studies on foam films properties and characteristics, parameters affecting foam stability together with the rupture of films between bubbles under dynamic condition will also be investigated.

COMSOL Multiphysics 5.3 was used to develop a model and run the simulation in order to investigate the correlation between stability of foam and streaming potential signals in foam injection process. The COMSOL software used were available for academic purposed. The numerical model of electrokinetic and foam stability was validated by using FEM. Therefore, the result obtained from this numerical simulation was compared with the outcome from the experimental works.

1.5 Significance of the Study

This research look into monitoring the changes in behaviour of foam during foam injection process which contributes to the changes of streaming potential signals. From this research, parameters affecting the stability of foam in foam injection process have also been identified.

Based on the findings from this simulation study, the application can be implemented in the real field which can give values to the oil and gas industry. A predictive numerical model of foam injection process is important for efficient process design and timely project evaluation. In addition, monitoring foam progression in EOR is necessary to ensure the process is effective or not. Extensive field application of foam in EOR requires appropriate project design, careful evaluation of reservoir candidates and process optimization to ensure the project success, both economically and technically.

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