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Foam sweep in fractures for enhanced oil recovery

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Dedicated to Professor Ivan B. Ivanov (LCPE, University of Sofia) on the occasion of his 70th birthday.

Abstract

A theory for foam flow in a uniform fracture was developed and verified by experiment. The apparent viscosity was found to be the sum of contributions arising from liquid between bubbles and the resistance to deformation of the interfaces of bubbles passing through the fracture. Apparent viscosity increases with gas fractional flow and is greater for thicker fractures (for a given bubble size), indicating that foam can divert flow from thicker to thinner fractures. This diversion effect was confirmed experimentally and modeled using the above theory for each individual fracture. The amount of surfactant solution required to sweep a heterogeneous fracture system decreases greatly with increasing gas fractional flow owing to the diversion effect and to the need for less liquid to occupy a given volume when foam is used.

Keywords: Foam; Bubbles; Fractures; Homogeneous; Heterogeneous; Apparent viscosity; Sweep

1. Introduction

Foam in porous media is a dispersed gaseous phase within a continuous aqueous phase comprised mainly of thin films known as lamellae. The lamellae are stabilized by adsorption of surfactant at the gas/liquid interfaces [1].

Because foam has an effective viscosity much higher than that of gas, it has been investigated as a method for improving sweep efficiency in processes where gases such as steam or supercritical CO_2 are injected to improve oil recovery from underground formations. Foam can reduce viscous fingering and gravity override caused by the low viscosity and density of the gas. Moreover, since fluids flow preferentially into layers of high permeability in a heterogeneous formation, foam is preferentially formed there and greatly increases local resistance to flow, thereby diverting injected fluids to zones of lower permeability and improving process efficiency.

The same potential advantages of using foam exist for surfactant and alkaline/surfactant processes for enhanced oil recovery except that gravity override is a less serious problem when surfactant solutions are injected. An additional advantage is that surfactant is already used in the basic process, so that additional chemical costs are low. One laboratory study of the possible use of foam in such processes for oil recovery and one successful field test by alkaline/surfactant/polymer/foam flooding have been reported [2,3]. Foam was used successfully a few years ago to improve sweep efficiency in a field test of a surfactant process for removing a chlorinated solvent from a sandy ground water aquifer [4]. Subsequently, the process was applied successfully to the remaining contaminated panels.

In this paper, we consider foam to improve efficiency of a surfactant process for oil recovery in a reservoir consisting of multiple fractures separating matrix blocks where oil is retained by capillarity and/or wettability. The injected surfactant solution enters the fractures, from which it penetrates the matrix blocks to release the oil. For instance, Hirasaki and Zhang [5] showed in a laboratory study that a solution of anionic surfactants in an alkaline solution could alter wettability and reduce interfacial tension in a matrix sample from a carbonate reservoir, releasing oil to flow upward by gravity into the fractures, where it could be directed toward production wells. But fracture systems have a broad distribution of fracture thicknesses. The thicker fractures will act as thief zones for the injected fluid. As a result, little of it will reach the thinner fractures. Foam provides a means to increase resistance to flow in the thicker

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Nomenclature

b	fracture aperture
b_i	aperture of fracture i
D_B	equivalent bubble diameter
FWR	foam-water ratio
f_g	gas fractional flow
K	crowding factor
K_I	internal circulation effect factor
k_i	permeability of fracture i
L	length of fractures
l	layer number
M_i	mobility ratio in fracture i
N	number of swept fractures
N_L	total number of fractures
∇p	pressure gradient
Δp	pressure difference
$\Delta p_{dynamic}$	dynamic pressure drop
PV	pore volume
LPV	injected liquid pore volume
Q_i	flow rate in fracture i
R	capillary radius
r_B	equivalent bubble radius
r_c	radius of curvature
Re	reynolds number
TPV	total pore volume
U	velocity of bubbles
V	aperture variance
v_i	velocity in layer
w_i	width of fracture i
x_i	dimensionless front of foam in fracture i
z_i	dimensionless hypothetical front of foam outside fracture i
σ	surface tension
ϕ	volume fraction
ϕ_{max}	dense random packing limit volume fraction
ρ^{liq}	density of liquid
μ_{app}	total apparent viscosity
$\mu_{app,i}$	apparent viscosity of displacing fluid in fracture i
μ_{app}^{liq}	apparent viscosity from liquid contribution
μ^{liq}	viscosity of pure fluid
μ_c	viscosity of continuous phase
μ_d	viscosity of dispersed phase
μ_i	apparent viscosity of fluid in fracture i
μ_r	relative viscosity
μ_{shape}^{liq}	apparent viscosity from bubble deformation

fractures and divert injected surfactant solution to the thinner fractures.

Two kinds of heterogeneous systems have been used in previous laboratory studies to investigate the ability of foam to improve sweep efficiency in parallel cores with differing permeabilities. The cores can be either isolated or placed in contact where cross flow can occur, e.g., in composite cylindrical cores. As indicated below, some of the studies have dealt with gas injection, others with injection of acid solutions to increase permeability.

Casteel and Djabbarah [6] used two parallel Berea cores with a 6.4 permeability ratio. They compared the use of foam with the water-alternating-gas process and showed that foam was preferentially generated in the more permeable core and could divert CO_2 towards the less permeable core. Llave et al. [7] obtained similar results with parallel cores with a 4.6 permeability ratio. Zerhboub et al. [8] studied matrix acidizing in a stratified system. They also showed clearly the effect of foam diversion. All these experiments, performed with parallel cores, considered only the case of porous media, which were not in capillary contact, so that crossflow was prohibited.

Yaghoobi et al. [9] used a short composite cylindrical core to study the influence of capillary contact. They observed a reduction of mobility in the higher permeability zone and called it "SMR", selective mobility reduction.

Siddiqui et al. [10] investigated the diversion characteristics of foam in Berea sandstone cores of contrasting permeabilities. They found that the diversion performance strongly depended on permeability contrast, foam quality and total flow rate.

Bertin et al. [11] studied foam propagation in an annularly heterogeneous porous medium having a permeability ratio of approximately 70. Experiments were performed with and without crossflow between the porous zones. In situ water saturations were measured continuously using X-ray computed tomography. They observed that foam fronts moved at the same rates in the two porous media if they were in capillary contact. On the other hand, when crossflow was prohibited due to the presence of an impervious zone between the layers, gas was blocked in the high permeability zone and diverted towards the low permeability core.

Osterloh and Jante [12] identified two distinct foam-flow regimes: a high-quality (gas fractional flow) regime in which steady-state pressure gradient is independent of gas flow rate, and a low-quality regime, in which steady-state pressure gradient is independent of liquid flow rate. In each regime foam behavior is dominated by a single mechanism: at high qualities by capillary pressure and coalescence [12], and at low qualities by bubble trapping and mobilization [13]. Cheng et al. [14] found that foam diversion is sensitive to permeability in high quality regime and insensitive to permeability in low quality regime. But in the low quality regime the harmful effect on diversion from crossflow is much less.

Nguyen et al. [15] conducted experiments to study foam-induced fluid diversion in isolated and capillary-communicating double layer cores. They found that there existed a threshold injection foam quality below which foam no longer invaded the low permeability layer. This threshold depends on the permeability contrast and foam strength in the high permeability layer. The use of foam below the threshold quality is appropriate in foam acid diversion, where the presence of foam in the high permeability layer helps control the relative acid permeability, and acid can still penetrate the low permeability layer without resistance of foam.