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Modelling foam improved oil recovery within a heterogeneous reservoir

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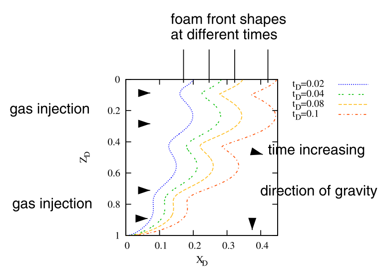
HIGHLIGHTS

- Pressure-driven growth model for foam improved oil recovery is considered.
- Reservoir is heterogeneous (stratified) and possibly also anisotropic.
- Heterogeneity produces convexities and concavities in the foam front.
- Concavities focus into corners that propagate differently from the rest of the front.
- Exceedingly anisotropic systems give sharply-curved concavities but not corners.

GRAPHICAL ABSTRACT



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ABSTRACT

The displacement of foam within a heterogeneous reservoir during foam improved oil recovery is described with the pressure-driven growth model. The pressure-driven growth model has previously been used to study foam motion for homogeneous cases. Here the foam model is modified in such a way that it includes terms for variable permeability. This model gives the evolution of the foam motion over time and the shape of the foam front, a wet foam zone between liquid-filled and gas-filled zones. The foam front shape for a heterogeneous or stratified reservoir develops concave and convex regions. For shapes such as these, the numerical solution of pressure-driven growth requires special numerical techniques, particularly in the case where concavities arise. We also present some analysis of the level of heterogeneity and how it affects the displacement, the shape of the front developing a set of concave corners. In addition to this we consider a heterogeneous and isotropic reservoir, in which case the foam front can sustain concavities, without these concavities having the same tendency to develop into corners.

1. Introduction

Only a fraction of oil in a petroleum reservoir can be extracted under the reservoir's own pressure. To maintain the flow of oil, fluids must be injected into the reservoir to maintain the pressure. Owing to their special rheological properties foams are able to improve sweep efficiency during oil production processes from underground formations compared to other injection fluids [1]. Foams achieve this higher efficiency sweep efficiency by reducing gas mobility which, prevents injected gas from simply rising to the top of the reservoir where it would fail to displace the oil; and also suppresses viscous fingering, whereby injected fluid would simply follow established flow paths. However, many studies have focused

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on homogeneous formations even when in real fields heterogeneous conditions are found [2,3]. A heterogeneous formation has variable permeability [4]. Therefore, the flow of fluids, and in this specific case, of foams is affected by this difference in permeability.

There are some laboratory and simulation studies on heterogeneous reservoirs which give insight into the advantage of using foam as a displacing fluid for oil recovery [2,5–10]. They have found that foam is able to divert the gas flow from high permeability regions towards zones with lower permeability [2,8–10].

Here we present a simulation study about the flow of foams within a heterogeneous reservoir. We have studied previously the displacement of foam within a homogeneous reservoir [11] (revisiting a model of Shan and Rossen [12]), and also two additional cases, one where the injection pressure is increased part way through the process and one taking into account the effect of surfactant slumping due to gravity [13,14].

The mathematical description of the system for the homogeneous case uses a foam model known as pressure-driven growth [11,12]. The model computes the advance of a foam front which forms the boundary between liquid ahead and foam behind. Motion of the foam front is driven by pressure difference across the front, i.e. the difference between a driving injection pressure and the hydrostatic pressure in the liquid. The front speed falls as depth increases because the hydrostatic pressure rises. The front speed also falls the further the foam displaces: this is because most of the dissipation in the system occurs in a wet foam region where the foam meets the liquid, and this wet foam region thickens over time, but its thickness always remains much less than the distance over which the front itself propagates [11,12,15]. The two additional cases, mentioned above, i.e. increase in driving pressure and surfactant slumping, use a suitable modification of the same model [13,14]. Therefore, in a similar fashion, we propose some changes to the original pressure-driven growth model that will make it appropriate to describe the case of the heterogeneous reservoir.

The rest of this work is structured as follows: Section 2 describes the changes we have applied to the pressure-driven growth model to make it suitable for a heterogeneous reservoir. Section 3 presents results of the numerical solution of the system highlighting some numerical implementation issues. Quantitative comparison between homogeneous and heterogeneous fronts is addressed in Sections 4 and 5, which give insight into the behaviour of the heterogeneous displacement. We have also explored the case of a heterogeneous but anisotropic reservoir, this is shown in Section 6. Finally, Section 7 offers conclusions.

2. Pressure-driven growth for variable permeability

The sketch in Fig. 1 illustrates the system that is considered via the pressure-driven growth model here. The physical content of the pressure-driven growth model (regardless of whether in a homogeneous or heterogeneous case) is that the speed of a foam front is proportional to the net driving pressure difference across it, this being the difference between the injection pressure and the hydrostatic pressure in the reservoir. Since hydrostatic pressure grows linearly with depth, the net driving pressure decays as a straight line function with depth, falling to zero at a critical depth. For the description of the heterogeneous case, the pressure-driven growth model[1] has been modified in a simple way: basically this takes into account permeability variation.

We describe relative changes in permeability with the help of a sinusoidally varying function, given below, which represents

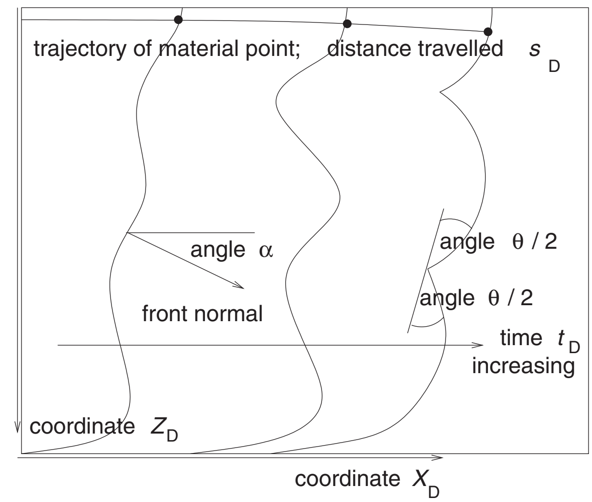

Fig. 1. Schematic for the foam front displacement in a two-dimensional heterogeneous reservoir (in terms of X_D vs Z_D coordinates) as function of time. Snapshots of the foam front at different times t_D are sketched. Here s_D is the distance travelled by a material point on the front, and α is the angle between the normal to the front and the horizontal. Permeability differences affect the shape of the foam front (causing it to develop concavities and convexities), and are described using Eq. (3) or (4). A sharp concave corner is considered to have formed when the angle θ through which the front tangent turns at the concavity exceeds a certain critical value.

the reservoir heterogeneity and is included within the equations describing the speed of the foam displacement.

Therefore the equations that apply in this case for horizontal and vertical components of velocity are[2]:

$$\frac{dX_D}{dt_D} = \frac{(1 - Z_D)\cos\alpha}{s_D} J(Z_D) \quad (1)$$

$$\frac{dZ_D}{dt_D} = \frac{(1 - Z_D)\sin\alpha}{s_D} J(Z_D) \quad (2)$$

where to illustrate the model $J(Z_D)$ can be chosen to be one of the following functions:

$$J(Z_D) = 1 + k_s \sin(2\pi n_s Z_D) \quad (3)$$

$$J(Z_D) = 1 - k_s \sin(2\pi n_s Z_D) \quad (4)$$

X_D is the horizontal position of a material point in a rectangular reservoir, Z_D the vertical position downwards, $1 - Z_D$ represents the decay of net driving pressure with depth, t_D is time, s_D is the distance material points on the front travel, α the angle giving the orientation of the front normal with respect to the horizontal, k_s is the amplitude of the heterogeneity variation about the mean (a factor less than unity), and n_s is the number of low and high permeability layers (for simplicity taken to be an integer). The reason for choosing a sinusoidal variation for the spatial variation of the permeability is so that the wavelength of the sinusoid can match the length scale of the layers in a heterogeneous stratified reservoir.

The above equations need to be solved with suitable boundary and initial conditions. The boundary condition is that motion needs to be horizontal along the top of the reservoir, so that $\alpha = 0$ at $Z_D = 0$. The initial condition is that the front is initially vertical and located at $X_D = 0$ for all Z_D. In addition s_D is initially zero for all material points, but grows as those material points displace.

Contrary to the convex shape expected for displacement in a homogeneous reservoir, in the present case the foam front shape

[1] Refer to [11,12] for the mathematical description of the model for constant permeability.

[2] These equations are in dimensionless form. Dimensional equations for the original system and their conversion to the dimensionless version are given in Appendix A.