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Foam front displacement in improved oil recovery in systems with anisotropic permeability

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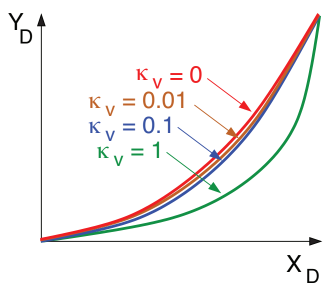
HIGHLIGHTS

- Foam front propagation in an oil reservoir is considered via pressure-driven growth.
- Strong anisotropy (vertical permeability much less than horizontal) is assumed.
- Uniform vertical migration superposed upon primarily horizontal front motion.
- Early-time front shape very insensitive to vertical to horizontal permeability ratio.
- At long times front shape is quasisteady, and sensitive to permeability ratio.

GRAPHICAL ABSTRACT



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ABSTRACT

A foam front propagating through an oil reservoir is considered in the context of foam improved oil recovery. Specifically the evolution of the shape of a foam front in a strongly anisotropic reservoir (vertical permeability much smaller than horizontal permeability) is determined via the pressure-driven growth model. The shape of the foam front is demonstrated to be extremely close to that predicted in the limiting case of a reservoir with no vertical permeability whatsoever, in particular any deviations from this shape are found to be second order in the ratio of vertical to horizontal permeabilities. Material points used to represent the foam front shape are shown to exhibit a uniform downward vertical motion, with a vertical velocity component which is proportional to the ratio of vertical to horizontal permeabilities. As the material points in question migrate downwards, they are replaced by new material points arriving from higher up, representing a long-time asymptotic solution for the front shape. This long-time asymptotic shape is sensitive to the ratio of vertical to horizontal permeabilities, with the foam front sweeping the reservoir less effectively as this ratio decreases.

1. Introduction

During the oil and gas production process, oil and gas reservoirs gradually become depleted over time: as oil is extracted from the reservoir, the pressure inside the reservoir declines to the point at which it is no longer possible to extract any more oil under the reservoir's own internal pressure. Subsequently it is possible to inject fluids into the reservoir to raise the reservoir pressure again, and thereby enhance or improve production [1]. The injected fluid moves from an injection well to a production well, pushing along the reservoir's oil as it moves. One candidate fluid for injection is foam [2–4], which is believed to have a number of beneficial flow

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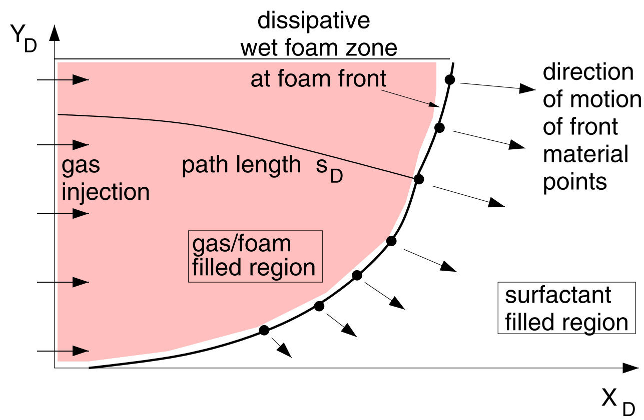

Fig. 1. Definition sketch for pressure-driven growth. The dissipative wet foam zone at the foam front separates surfactant liquid downstream from a gas filled region upstream. The front at any instant in time t_D is represented by a set of material points (indicated by black circles) with coordinates (X_D, Y_D), these material points having displaced through a path of length s_D.

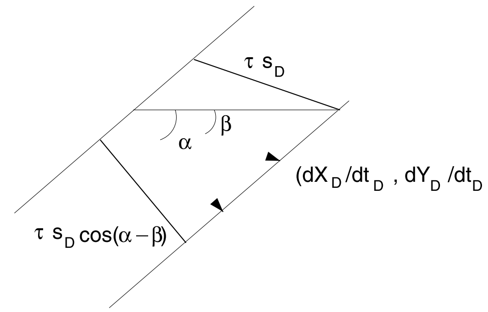

Fig. 2. Zoomed view of a local section of foam front, where the normal to the front is at angle α from the horizontal. The velocity vector of a material point (dX_D/dt_D, dY_D/dt_D) is at angle β from the horizontal. Here $\beta < \alpha$ in an anisotropic system so the motion of material points is oblique to the front normal. The thickness of the front measured along the velocity direction is τs_D where τ is a small parameter and s_D is the path length travelled. The thickness of the front measured along the front normal is a factor $\cos(\alpha - \beta)$ smaller.

properties in the improved oil recovery context. One of these beneficial properties is [5] is the comparatively low mobility of foam, implying in turn a tendency to displace fairly uniformly through a porous medium (unlike more mobile injection fluids, such as e.g. water or air, that could be channelled along just a limited number of flow paths via fingering-type instabilities). Another beneficial property of foam [5] is trapping of foam films in pores that might have already been reached by preceding injection fluids (implying an ability to access parts of the reservoir which are not blocked by trapped films and which might not have been previously reached). For example, injection fluids such as water or air access large pores more readily than small ones. For injection utilising foam however, foam films might remain trapped in large pores but can collapse (and hence are not trapped) in smaller pores, since capillary pressure effects, causing the films to drain and collapse [5], are more significant in small pores.

In order to exploit foam injection operations more effectively, there has been considerable effort in the petroleum engineering community to simulate the foam improved oil recovery process using a number of rather sophisticated computer models [6–12]. An alternative approach introduced by Shan and Rossen [5], which has recently been dubbed pressure-driven growth [13], looks at a somewhat simpler phenomenological model.

As is more fully explained in [5,13], the pressure-driven growth model attempts to represent the so called surfactant alternating gas process, which involves injecting first surfactant into the oil and gas reservoir followed by injecting gas (e.g. steam, carbon dioxide, nitrogen). A foam front is then formed in situ at the boundary between the surfactant and injected gas: see the sketch in Fig. 1. The foam front displaces over time under the action of a net driving pressure: this is the difference between an injection pressure and a hydrostatic pressure.

The net driving pressure is balanced by dissipative forces, associated with moving the foam front through the reservoir. The dissipation tends to be localized in a wet foam zone where injected gas meets surfactant: the thickness of this zone might be as little as one percent of the distance over which the front itself has displaced [13]. As a first approximation then, the shape of the foam front (i.e. the shape of the wet foam zone) can be represented as a 1-D curve in a 2-D domain. The pressure-driven growth model specifically tracks the motion over time of material within this wet foam zone, with the shape of the foam front itself being reconstructed by tracking the motion of a multitude of material points covering the length of the front.

Some comments are pertinent. Since the hydrostatic pressure itself grows with depth, the net driving pressure diminishes with depth. This implies that points higher up on the foam front move further and faster than points lower down (see Fig. 1). Moreover the implication is that there is a critical depth at which injection pressure and hydrostatic pressure come into balance: the foam front cannot advance beyond that depth.

Although the pressure-driven growth model was originally conceived to describe homogeneous and isotropic reservoirs [5], reservoirs are generally heterogeneous and anisotropic. The role of heterogeneity and anisotropy is unsurprising given that oil and gas bearing reservoirs are found within sedimentary rock formations, and such formations tend to be stratified into layers, the properties of each layer being sensitive to the conditions under which it was formed. During foam improved oil recovery, heterogeneity can affect the foam front shape by offsetting (or partly offsetting) the aforementioned tendency of points lower down on the front to move more slowly than those higher up. Anisotropy meanwhile causes points to move not normal to the foam front, but instead obliquely: see Fig. 2. It soon became apparent [13] that the pressure-driven growth model could predict interesting behaviour in the case of stratified reservoirs that were either heterogeneous [14] or anisotropic [15] or both. Specifically in the case of reservoir heterogeneity [14], solutions of the model can develop sharp concave corners (i.e. regions over which the orientation of the front changes quite suddenly over a comparatively small distance), and much of the challenge of obtaining solutions of the model numerically involves strategies for dealing with these concave corners. Particularly when heterogeneity is coupled to anisotropy, these sharp corners are found to move in very counter-intuitive ways [15].

The purpose of the present work is to consider anisotropy in the absence of heterogeneity, a situation which was first considered by de Velde Harsenhorst and co-workers [16,17]. The key parameter governing anisotropy is the ratio between vertical and horizontal permeability of the reservoir. We denote this permeability ratio by the symbol κ_ν and consider that its value can vary between zero and unity: e.g. [16] considered values of κ_ν equal to 0, 0.01, 0.1 and 1. Specifically we set out in what follows to explain a curious result obtained by [16] when front shapes are computed numerically (details of the numerical technique and the results it produces are discussed in the cited reference). The finding (see the schematic sketch in Fig. 3) was that the numerical data for $\kappa_\nu = 0.01$ and $\kappa_\nu = 0.1$ reported by [16] are very close to an analytical solution for the front shape applicable in the limit $\kappa_\nu = 0$. However numerical data for $\kappa_\nu = 1$ differed quite substantially from these other cases.

The rest of this work is laid out as follows. Section 2 describes the governing equations for pressure-driven growth in the