Transport in Porous Media **44:** 1–32, 2001.

Three-Phase Capillary Pressure and Relative Permeability Relationships in Mixed-Wet Systems

M. I. J. VAN DIJKE, S. R. MCDOUGALL and K. S. SORBIE
Department of Petroleum Engineering, Heriot-Watt University, Edinburgh EH14 4AS, Scotland, U.K.

(Received: 6 July 1999; in final form: 18 April 2000)

Abstract. A simple process-based model of three-phase displacement cycles for both spreading and non-spreading oils in a mixed-wet capillary bundle model is presented. All possible pore filling sequences are determined analytically and it is found that the number of pore occupancies that are permitted on physical grounds is actually quite restricted. For typical non-spreading gas/oil/water systems, only two important cases need to be considered to see all types of allowed qualitative behaviour for non-spreading oils. These two cases correspond to whether water or gas is the 'intermediate-wetting' phase in oil-wet pores as determined by the corresponding contact angles, that is, $\cos\theta_{\rm gw}^{\rm o} > 0$ or $\cos\theta_{\rm gw}^{\rm o} < 0$, respectively. Analysis of the derived pore occupancies leads to the establishment of a number of relationships showing the phase dependencies of three-phase capillary pressures and relative permeabilities in mixed-wet systems. It is shown that different relationships hold in different regions of the ternary diagram and the morphology of these regions is discussed in terms of various rock/fluid properties. Up to three distinct phase-dependency regions may appear for a non-spreading oil and this reduces to two for a spreading oil. In each region, we find that only one phase may be specified as being the 'intermediate-wetting' phase and it is only the relative permeability of this phase and the capillary pressure between the two remaining phases that depend upon more than one saturation. Given the simplicity of the model, a remarkable variety of behaviour is predicted. Moreover, the emergent three-phase saturation-dependency regions developed in this paper should prove useful in: (a) guiding improved empirical approaches of how two-phase data should be combined to obtain the corresponding three-phase capillary pressures and relative permeabilities; and (b) determining particular displacement sequences that require additional investigation using a more complete process-based 3D pore-scale network model.

Key words: three-phase flow, capillary pressure, relative permeability, capillary bundle, mixed-wet, spreading coefficient, saturation-dependency, pore occupancy, process-based model.

1. Introduction and Literature Review

The study of three-phase flow in porous media is important in many subsurface processes such as those which occur in oil recovery and in aquifer remediation involving non-aqueous phase liquids (NAPLs). The principal multiphase flow parameters that appear in the governing transport equations are the three-phase capillary pressures and relative permeabilities. These quantities, especially the three-phase relative permeabilities, have been the subject of much study over the past 40 years although much still remains to be understood about the behaviour of three-phase systems. The problem is compounded if we consider porous media of non-uniform wettability. In this paper, we focus on three-phase capillary controlled flow in simplified models of mixed-wet porous media.

In the context of petroleum recovery, Leverett and Lewis (1941) and Corey *et al.* (1956) presented early discussions of the issues involved in three-phase flow. Since that time, a number of experimental studies of three-phase flow, principally measuring relative permeabilities, have appeared in the literature although such measurements are far from routine (Naar and Wygal, 1961; Saraf *et al.*, 1982; Grader and O'Meara, 1988; Oak, 1990, 1991; Oak *et al.*, 1990; Kalaydjian *et al.*, 1993; Nordtveldt *et al.*, 1996). The difficult and time-consuming nature of these measurements has meant that a full parameteric study of all of the factors affecting three-phase flow in porous media has not been possible. Since so few factors are varied in any particular study and conditions change from one study to another, it is difficult to draw general conclusions from this body of experimental work. This is further complicated when petroleum reservoir rocks are considered, due to the difficulty in characterising the wettability states that such systems can adopt (Morrow, 1990; Cuiec, 1991; Jerauld, 1997; Jerauld and Rathmell, 1997).

The extreme difficulty in measuring three-phase relative permeabilities (and capillary pressures), has led to a number of attempts to derive empirical expressions for the three-phase relative permeability isoperms by combining the two phase data in various ways (Stone, 1970, 1973; Dietrich and Bondor, 1976; Delshad and Pope, 1989; Fayers, 1984; Fayers and Mathews, 1984; Baker, 1988; Balbinski *et al.*, 1997; Blunt, 1999). The early work of Stone (1970, 1973) has been both criticised and extended by later workers in the previous reference list. This approach is based partly on the fact that the three-phase flow parameters must limit appropriately to the various combinations of two phases which can occur. For example, in an oil/water/gas system, such as may be found in a petroleum reservoir, the three-phase relative permeability should limit correctly to the various two-phase oil/water, gas/oil and gas/water relative permeabilities. This fact has been used recently by both Hustad and Hansen (1996) and Blunt (1999) as the basis for a consistent three-phase relative permeability model. In addition to consistency, the correct phase trapping characteristics must be predicted by such empirical models and, for this purpose, early models due to Land (1968) and Carlson (1981) have been used. Recently, Skauge and Larsen (1994) have proposed more elaborate models for phase trapping in WAG (water-alternating-gas) processes in order to explain experimentally observed behaviour. The issue of residual oil determination in three-phase empirical models is also discussed by Balbinski *et al.* (1997) and Blunt (1999). In the groundwater/NAPL aquifer remediation literature, there have also been several attempts to predict three-phase flow parameters in various empirical ways (Lenhard, 1987, 1992; Parker *et al.*, 1987; Parker and Lenhard, 1990).

In empirical models of three-phase relative permeability, there is often little acknowledgement of the underlying pore-scale displacement physics. Therefore,