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Flow regime associated with vertical secondary migration

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ABSTRACT

Secondary migration is defined as the movement of hydrocarbons through relatively permeable rocks from source to trap: a two-phase flow within a porous medium. Depending on the geometry and capillary pressure distributions of carrier beds, secondary migration has both vertical and lateral components. The present paper focuses on that part of the migration where the movement is mainly vertical. Its objective is to propose a description of the dynamics governing the vertical part of secondary migration based on the main physical aspects of two-phase flow in a homogeneous porous medium. The study is illustrated by laboratory observations performed in a vertical, 2-D Hele-Shaw cell filled with a transparent porous medium where the flow of dyed oil invading a wetting fluid is visually observed. These observations help us to understand the effect of buoyant, capillary and viscous forces on the resulting flow, the relative importance of which is characterized by non-dimensional numbers. Extrapolating these observations to natural media, it is proposed that vertical secondary migration can be described as a percolation of disconnected and vertically-elongated stringers. These stringers do not move continuously but as a succession of snap-off and re-feeding events which result in a jerky upward movement. Using parameters characterizing the physical properties of the fluid and of the porous medium, the geometry and the dynamic behavior of the stringers are estimated. The width of stringers occurring during secondary migration in geological media is centimetric and their vertical size ranges from several centimeters to a few meters. An upper limit of the mean upward velocity of stringers is proposed, as well as an estimate of their spatial density and of the minimum, average horizontal distance (decametric) between two stringers. The stringers are sparsely distributed, resulting in a low average oil loss and a high efficiency of the vertical migration process.

1. Introduction

Secondary migration is the process by which oil expelled from low permeability source rocks, finds a path through carrier beds toward accumulation and traps (Schowalter, 1979; England et al., 1987; Dembicki and Anderson, 1989; England et al., 1991; England, 1994; Welte et al., 2000). There is a general consensus that secondary migration occurs as a separate phase flow through the water-filled pores of the carrier (Mann, 1997), although there are alternative hypotheses such as migration in solution (Selley, 1998); this can work only for lighter components of hydrocarbons, partly miscible with the surrounding water.

Once expelled from source rocks, the flow of hydrocarbons in porous rocks can be divided into two phenomena. Due to their low density, hydrocarbons expelled into low capillary pressure units such as sandstones rise mainly vertically until they encounter capillary pressure barriers such as mudstones. At this point, lateral migration of hydrocarbons with an important horizontal component can occur. The present paper is focussed on that part of migration where the movement is mainly vertical. Its objective is to propose a description of the dynamics governing the vertical part of secondary migration, based on the main physical aspects of two-phase flow in porous media. The study of lateral migration imposed by the presence of sealing rocks and resulting in important horizontal movement has been the subject of other experimental studies (Catalan et al., 1992; Thomas and Clouse, 1995; Yan et al., 2012a).

From a physical point of view, vertical secondary migration can be reduced to a specific case of two-phase flow where two

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immiscible fluids are flowing in the porous space. More precisely, since the porous medium is initially saturated with water wetting the grains of the porous medium and the grain surfaces have a water-wetting behavior, secondary migration is a process of invasion by a non-wetting fluid (Dembicki and Anderson, 1989; Catalan et al., 1992; Carruthers and Ringrose, 1998; Luo et al., 2004). A very specific property of this flow is that the invading fluid has a density lower than that of the expelled fluid. Buoyancy forces therefore play a major role as the motor of this invasion, with capillary and viscous forces providing opposing drag forces. The relative importance of these various forces may be characterized by non-dimensional numbers (Wilkinson, 1984; Hirsch and Thompson, 1995; Thomas and Clouse, 1995; Meakin et al., 2000). Here, we are only concerned with two-phase flow of oil and water and the possible presence of gas is not discussed.

The main objective of this paper is to demonstrate the main physical aspects of flow as observed in physical experiments and to synthesize studies concerning two-phase flow. Orders of magnitude of the relevant physical parameters that may occur in the subsurface during natural secondary migration are obtained. In order to illustrate the present study, we make use of laboratory observations performed in a vertical Hele-Shaw two-dimensional (2D) cell filled with a transparent porous medium. Dyed oil is injected at the bottom of the cell, allowing direct visualization of the flow. The description of the cell is given in Appendix A. The processes occurring in the cell give a visual illustration of the statements used here to characterize the flow properties.

The geometry of the flow, its dynamics and its time scales are discussed as a function of non-dimensional numbers describing the relative importance of the forces acting at micro-scale. On the basis of these non-dimensional numbers, an extrapolation of the flow characteristics to the actual conditions of natural hydrocarbon migration is proposed. This extrapolation shows that the vertical migration of hydrocarbon leads to the formation of disconnected oil stringers, the geometry of which can be assessed. The velocity of these stringers, their pathways and their evolution with time through possible fragmentation and re-connection, are fundamental questions on which experimental and theoretical physics give interesting clues.

Table 1
Parameters applicable to the laboratory experiments illustrated by Fig. 1–4.

1-1) Parameters for the experiment shown on Figure 1

	Variable	Unit	Value	
g	Gravity acceleration	m s^{-2}	9.81	
$\Delta\rho$	Density difference	kg m^3	208	
γ	Surface tension	N m^{-1}	0.0289	
2ε	Pore diameter	mm	0.6–0.8	
Bo	Bond number		8.65E-3	
μ	Viscosity of oil	Pas	0.00169	
Φ	Porosity		0.36	
F	Coefficient for permeability		395	
k	Permeability	m^2	3.10E-10	
			Figure 1a	Figure 1b
	Injection rate	ml/mn	0.1	3
q	Injection velocity at 5 cm of point source	m s^{-1}	3.54E-6	1.06E-4
Ca	Capillary number		8.17E-5	2.45E-3

1-2) Parameters for the experiment shown on Figure 2

	Variable	Unit	Value		
	Injection rate	ml/mn	0.5		
q	Injection velocity at 5 cm	m s^{-1}	1.77E-5		
Ca	Capillary number		4.09E-4		
			Figure 2a	Figure 2b	Figure 2c
2ε	Bead diameter	mm	1.0–1.2	1.2–1.5	1.5–2.0
Bo	Bond number		2.14E-2	3.17E-2	5.41E-2
ξ	Finger width	mm	4.95	4.82	4.64

1-3) Parameters for the experiment shown on Figure 3

	Variable	Unit	Value
	Injection rate	ml/mn	0.5
q	Injection velocity at 5 cm	m s^{-1}	1.77E-5
Ca	Capillary number		4.09E-4
2ε	Bead diameter	mm	1.5–2.0
Bo	Bond number		5.41E-2
$\zeta = \varepsilon$/Bo	Finger height	mm	16.2

1-4) Parameters for the experiment shown on Figure 4

	Variable	Unit	Value
	Injection rate	ml/mn	0.05
q	Velocity in the main part	m s^{-1}	1.11E-6
Ca	Capillary number		2.75E-5
2ε	Bead diameter	mm	0.8–1.0
Bo	Bond num.		1.43E-2
ξ	Stringer width	mm	5.1
ζ	Stringer height	mm	31.5
V/Φ	Instantaneous Velocity	m s^{-1}	1.73E-3
D	Distance between stringers	m	2.8

2. Micro-physics of oil migration and non-dimensional numbers Bo and Ca

The motor of secondary migration is buoyancy, resulting from the lower density of hydrocarbons compared to surrounding water. Forces slowing the movement are viscosity (interaction with porous framework) and capillarity due to surface forces at the interfaces between the various fluids. These depend on a large number of parameters characterizing both the porous medium and the fluids. Table 1 gives the main parameters relevant to the experimental results used as a support for this study (displayed on Figs. 1–4). Table 2 gives the corresponding parameters applicable to natural migration as derived from generally accepted values for natural reservoirs. The fluid properties (viscosity, surface tension and density difference) correspond to typical properties expected in natural conditions (Hantschel and Kauerauf, 2007) and are about the same in both experimental and natural cases (Tables 1 and 2). This is not the case for the pore size of the porous medium – and for the related parameters – which is larger in experiments than those in natural conditions. As explained below, this discrepancy is associated with the requirements of short-term laboratory experiments.

Despite the differences in experimental and subsurface conditions, the understanding of the micro-physics and the introduction of characteristic ratios allows us to reconcile results from experimental physics to natural phenomena. In fact, the characterization of two phase flow in porous media can be simplified by the introduction of two non-dimensional numbers (Lenormand, 1985; Wilkinson, 1984, 1986), as presented below.

2.1. The Bond number

The Bond number Bo characterizes the ratio of gravity forces to capillarity at the pore scale. It is given by

$$\mathrm{Bo} = \Delta\rho\, \varepsilon^2 g/\gamma, \tag{1}$$

$\Delta\rho$ being the density difference, ε the pore size, γ the surface tension and g the acceleration of gravity (m s^{-2}).

For the experimental cell, the parameters are presented in Table 1 and, for natural migration, in Table 2. The main fluid parameters characterizing the flow are the density difference $\Delta\rho$ between water and oil and the oil-water interfacial tension γ; average values $\Delta\rho = 0.2 \times 10^3$ kg m^{-3} and $\gamma = 0.03$ N m^{-1} are chosen as