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Effect of sample shape on counter-current spontaneous imbibition production *vs* time curves

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ABSTRACT

Counter-current spontaneous imbibition experiments on porous media are usually carried out using cylindrical core samples. Sometimes the cores are sealed on some of the faces, and experiments then give production curves of significantly different duration and slightly different shape. Results can be correlated for rock properties (porosity and permeability) and fluid properties (viscosity and interfacial tension). A single overall scale factor is usually used to correlate for different core sizes and shapes. Although the real imbibition process is actually quite complicated, by making the approximations that there is (a) frontal displacement and (b) constant saturation behind the front, a simple analytical solution is possible. The analysis gives the production *vs* time function and a new core shape scale factor. These assumptions also allow the scale factors of Ma et al. [Ma, S., Morrow, N.R. & Zhang, X., 1997, J. Pet. Sci. Eng., 18, 165–178.] and Ruth et al. [Ruth, D., Mason, G. & Morrow, N.R., 2003, Proc. Soc. Core Analysts Symp., Pau, SCA2003-16, 1–12.] to be used to predict the shape of the production *vs* time curves. In order to challenge the predictions of the production *vs* time curves and the Ma, Ruth and new scale factors, counter-current spontaneous imbibition experiments were carried out with matched oil-saturated cores of different shape using brine to spontaneously displace the mineral oil. Amongst others, cylindrical cores with an axial hole were used with either the inner or outer cylindrical face open. These have radial geometry with imbibition into a contracting or expanding volume. Analysis of the experimental results with the new theory confirmed that the Ma and Ruth scale factors are good to excellent for most situations but that the new one is marginally better for extreme shape variations. The theory also predicts that all of the results should be linked by a universal properties factor (*G*). The variability of the *G* factor can be explained by some of the cores not having enough exposed surface and not enough rock depth. These factors seem to be of greater importance than the differences between the scale factors. For reproducible results it appears that a core should have an imbibition face area of at least 40 cm^2 and a thickness (open face to no-flow boundary) of at least 1 cm.

1. Introduction

Counter-current spontaneous imbibition occurs when a wetting fluid displaces a less-wetting fluid from the pore space of a porous medium. The wetting fluid imbibes into the pore space and the non-wetting fluid is expelled. Under these circumstances, the mass balance requirement means that the volumetric flows of the two fluids are locally everywhere equal but in opposite directions. Also, in some circumstances, particularly when the porous medium is initially filled with non-wetting phase, a saturation front is observed to advance through the system. A positive pressure has to build up at the dead end of the system and it is this pressure that pushes the non-wetting phase back through the invading wetting phase. Counter-current imbibition is believed to be a mechanism by which oil can be displaced from the rock in fractured reservoirs (Morrow and Mason, 2001).

Countercurrent imbibition in reservoir rocks is usually studied at the core level using cylindrical cores about 70 mm long and with a diameter of about 35 to 50 mm. A typical experiment consists of saturating a core with oil and then immersing it in brine. The expelled oil is collected and its volume is measured. Results are recorded as the total amount of oil produced at various time intervals. Attempts have been made to correlate results for very strongly water wet (VSWW) imbibition so that the effect of changing interfacial tension, rock porosity and permeability can be predicted (Mattax and Kyte, 1962). There are two additional factors — the viscosities of the two phases and the shape of the sample. This paper primarily addresses the latter

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Nomenclature

A	Area (m^2)
A_i	Area open to imbibition in the ith direction (m^2)
A_R	Area of the cylinder at a general radius, R (m^2)
C_{Ma}	Constant in Ma's equation (s/m^2)
C_{spread}	Factor determined by the breadth and shape of the pore size distribution
d	Core diameter (m)
f	Fraction of the core filled
F_f	Factor which is a function of the fraction of the core filled (m)
G_{Ma}	Physical properties factor for Ma's equation (s/m^2)
G_{Mason}	Physical properties factor for the equations presented here (s/m^2)
K	Permeability (m^2)
k_{rnw}	Relative permeability to the non-wetting phase
k_{rw}	Relative permeability to the wetting phase
L_c	Characteristic length (m)
L_{core}	Length of core in radial imbibition (m)
$L_{\max}$	Length of the core for linear imbibition (m)
M	Mobility factor ($Pa^{-1}\ s^{-1}$)
n	Total number of surfaces open to imbibition
P_c	Capillary pressure (Pa)
P_{cf}	Capillary pressure at the imbibition front (Pa)
P_{co}	Capillary pressure at the open face (Pa)
P_{nw}	Pressure in the non-wetting phase (Pa)
P_{w}	Pressure in the wetting phase (Pa)
q_{nw}	Flow of non-wetting phase (m^3/s)
q_{w}	Flow of wetting phase (m^3/s)
$q_{\mathrm{w},R}$	Flow passing through a cylindrical surface of radius R (m^3/s)
r_{mean}	Mean pore radius (m)
R_{f}	Radial distance of the front from the axis (m)
R	General radius (m)
R_{closed}	Radius of closed boundary in radial imbibition (m)
R_{f}	Radial distance of the front from the axis during radial imbibition (m)
R_{inner}	Radius of the inner open face for core with axial hole (m)
R_{nf}	Radius of the no-flow boundary for core with axial hole
R_{open}	Radius of open boundary in radial imbibition (m)
R_{outer}	Radius of open outer face for core with axial hole (m)
S_{wf}	Wetting phase saturation behind the front
S_{wi}	Initial wetting phase saturation
t	Time (s)
t_{D}	Dimensionless time
t_{end}	Time when imbibition ceases (s)
t_f	Time for fractional production, f
x	Distance (m)
x_{f}	Distance from the open surface to the saturation front (m)
x_i	Distance from the open surface to the no-flow boundary (m)
φ	Porosity
μ_{nw}	Viscosity of the non-wetting phase (Pa s)
μ_{w}	Viscosity of the wetting phase (Pa s)
σ	Interfacial tension (N/m)

Subscripts

Linear	One dimensional imbibition
Ma	Calculated from Ma's equation
Mason	Calculated from the equations presented here
Ruth	Calculated from Ruth's equation

factor. Frequently, cores used in experiments have all faces of the cylinder open to the invading phase. The experiments give rapid and reproducible results but the flow patterns are complex and, therefore, difficult to model. If the ends of the core cylinder are sealed then the flows become radial. The simplest case, however, reducing imbibition to a one-dimensional, linear situation, is to seal the outer surface plus one end, thus leaving one end open for the imbibition and production to take place. Because the shape of the sample makes a difference to both the time and the shape of the production *vs* time results, it would be convenient to be able to transform experimental results obtained from one core geometry into those from another (Behbahani et al., 2006). A function involving the core sample shape which has