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A generalized power-law scaling law for a two-phase imbibition in a porous medium

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ABSTRACT

Dimensionless time is a universal parameter that may be used to predict real field behavior from scaled laboratory experiments in relation to imbibition processes in porous media. Researchers work to nondimensionalize the time has been through the use of parameters that are inherited to the properties of the moving fluids and the porous matrix, which may be applicable to spontaneous imbibition. However, in forced imbibition, the dynamics of the process depends, in addition, on injection velocity. Therefore, we propose the use of scaling velocity in the form of a combination of two velocities, the first of which (the characteristic velocity) is defined by the fluid and the porous medium parameters and the second is the injection velocity, which is a characteristic of the process. A power-law formula is suggested for the scaling velocity such that it may be used as a parameter to nondimensionalize time. This may reduce the complexities in characterizing two-phase imbibition through porous media and works well in both the cases of spontaneous and forced imbibition. The proposed scaling-law is tested against some oil recovery experimental data from the literature. In addition, the governing partial differential equations are nondimensionalized so that the governing dimensionless groups are manifested. An example of a one-dimensional countercurrent imbibition is considered numerically. The calculations are carried out for a wide range of *Ca* and *Da* to illustrate their influences on water saturation as well as relative water/oil permeabilities.

1. Introduction

Imbibition is an important mechanism in oil recovery from water-wet fractured-matrix reservoirs subjected to water drive. Imbibition is defined as the displacement of the non-wetting phase (oil) by the wetting phase (water) with capillary force dominates other forces. Imbibition may be classified as countercurrent and cocurrent. In cocurrent imbibition, water forces oil out of the matrix, with both water and oil flows are in the same direction. Countercurrent imbibition, on the other hand, is when the wetting phase imbibes into the porous matrix (rock), displacing the non-wetting phase out from one open-boundary. Cocurrent imbibition has been reported by several authors (e.g., Pooladi-Darvish and Firoozabadi, 2000b) to be faster and more efficient than countercurrent imbibition. This may be because the whole exit area becomes available for the flow in the cocurrent imbibition rather than shared by the two fluids, as the case with countercurrent imbibition. Furthermore, the formulation of cocurrent imbibition suggests an additional convective term, which may be responsible for such an effect (McWhorter and Sunada, 1990; Pooladi-Darvish and Firoozabadi, 2000b, etc). However, countercurrent imbibition may sometimes be the only possible displacement mechanism for cases where the matrix region is completely surrounded by water in the fractures (Bourbiaux and Kalaydjian, 1990; Chimienti et al., 1999; Pooladi-Darvish and Firoozabadi, 2000b; Najurieta et al., 2001; Tang and Firoozabadi, 2001; El-Amin and Sun, 2011; El-Amin et al. 2013). Scaling laws of laboratory experiments are very important in shedding light on the behavior of similar real systems. The importance of this concept in petroleum engineering is the fact that oil recovery from reservoir matrix blocks, for example, can be predicted from experimental tests conducted on small-scale samples in laboratory. Laboratory results of oil recovery are usually presented as a function of dimensionless time. Dimensionless time is a universal parameter including several physical parameters. Generally, a good scaling practice is achieved when the chosen scaling parameters are such that the measured oil recovery may be represented as a single universal curve with less primary physical parameters. Scaling criteria for two-phase incompressible flow in porous media were first introduced by Rapoport (1955). He found that the saturation distribution may be represented as a function of dimensionless time. Many authors have paid attention to scaling methods of experimental data of imbibition in porous media in different setups (e.g., Hamon and Vidal, 1986; Ma et al., 1997; Babadagli, 1997, 2001; Tong et al., 2001; Zhou et al., 2002; Tavassoli et al., 2005; Li, 2007). Unlike these scaling models,

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Sadjadi and Rieger (2013) presented a scaling theory for the long time behavior of spontaneous imbibition in porous media consisting of interconnected pores with a large length-to-width ratio. Recently, a number of articles have been discussed scaling methods such as, Standnes (2009, 2010a, 2010b) and Schmid and Geiger (2013). In most of these scaling models the dimensionless time is formulated as a universal parameter collecting important primary parameters of the systems such as permeability, porosity, interfacial tension and fluids viscosities; which, generally, allows the oil recovery ratio to be presented as a function of the dimensionless time. Several authors have introduced different parameters on defining the dimensionless time. For example, Mattax and Kyte (1962) presented a scaling law for time, on their study of oil recovery by imbibition, in the form:

$$T=\left(\frac{K}{\varphi}\right)^{1/2}\frac{\gamma}{\mu_w L^2}t \tag{1}$$

where T [–] is the dimensionless time, γ [N/m] is the water–oil interfacial tension, K [m^2] and φ [dimensionless] are the permeability and the porosity of the porous medium, respectively, μ_w [Pa s] is the dynamic viscosity of the water, t [s] is imbibition time and L [m] is a characteristic or effective length given by (see for instance Yildiz et al. (2006))

$$L=\sqrt{V/\sum_{i=1}^{n}A_i/l_i} \tag{2}$$

where V [m^3] is the matrix block volume, A_i [m^2] is the area open to flow in the ith direction and l_i [m] is the distance from the open surface to a no-flow boundary. This equation may be used for general irregular matrix geometries. For simple geometries such as that of the experimental work of Tang and Firoozabadi (2001) and that of our proposed computational work, Eq. (2), reduces the characteristic length to the core length, i.e. the distance between the open-boundary to the no-flow boundary L, (see Fig. 1). Some works on complex geometries introduce intensive explanations on the use of Eq. (2) such as Yildiz et al. (2006). Eq. (1) indicates that oil recovery from different size cores with different fluids may be represented by one universal curve as a function of the dimensionless time. Gupta and Civan (1994) argued that the above formula did not take into consideration the effect of relative wettability of pore surface with respect to oil and water which is manifested by the contact angle, θ. Therefore they proposed including the contact angle into the expression of Mattax and Kyte (1962), such that

$$T=\left(\frac{K}{\varphi}\right)^{1/2}\frac{\gamma\cos\theta}{\mu_w L^2}t. \tag{3}$$

For strongly water-wet matrix, $0<\theta<90$ and for weakly water-wet matrix $90<\theta<180$, therefore we suggest the above

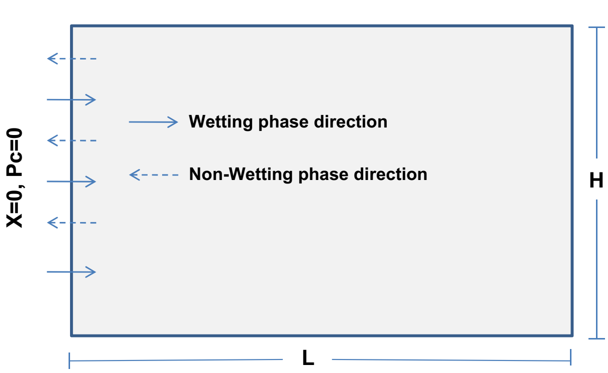

Fig. 1. Schematic diagram of the countercurrent imbibition.

expression to be written as

$$T=\left(\frac{K}{\varphi}\right)^{1/2}\frac{\gamma|\cos\theta|}{\mu_w L^2}t, \tag{4}$$

so that it is positive when used into the dimensionless time.

On the other hand, Ma et al. (1997) modified the Mattax and Kyte (1962) scaling law by including the viscosity of the non-wetting phase such that the nondimensional time takes the form,

$$T=\left(\frac{K}{\varphi}\right)^{1/2}\frac{\gamma}{\sqrt{\mu_w\mu_o}L^2}t \tag{5}$$

where μ_o [Pa s] is the oil dynamic viscosity. Cil et al. (1998) used the following scaling-law,

$$T=\left(\frac{K}{\varphi}\right)^{1/2}\frac{\gamma\cos\theta}{\sqrt{\mu_w\mu_o}L^2}t \tag{6}$$

which includes the absolute value of $\cos\theta$.

Tavassoli et al. (2005) reported that including both water and oil viscosities in the dimensionless time is a good scaling group and better than including water viscosity only. Zhou et al. (2002) correlated all the imbibition data for a wide range of mobility ratios with the scaling form,

$$T=\left(\frac{K}{\varphi}\right)^{1/2}\frac{\gamma}{L^2}\frac{\sqrt{\lambda_{rw}\lambda_{ro}}}{\sqrt{M}+(1/\sqrt{M})}t \tag{7}$$

where $\lambda_r=k_r/\mu$ is the characteristic mobility, $M=\lambda_{rw}/\lambda_{ro}$ is the mobility ratio. Li (2007) has introduced a scaling model includes wettability in scaling of spontaneous imbibition data. On the other hand, Morrow and Mason (2001) suggested, in their review, that imbibition rate may need to be used in the formulation of scaled group in order to highlight the role of system's dynamics.

Xie and Morrow (2000) highlighted that when capillary forces are sufficiently small, gravity segregation significantly affects oil recovery. Therefore, gravity needs to be included in the expression for dimensionless time as

$$T=\frac{K}{\varphi\sqrt{\mu_w\mu_o}L^2}\left(P_{ci}f(\theta)+\frac{\Delta\rho g L^2}{H}\right)t \tag{8}$$

where H is the sample height, $f(\theta)$ is the wettability factor, P_{ci} is a representative imbibition capillary pressure and is proportional to $\gamma/\sqrt{K/\varphi}$. It is noteworthy that this relationship reduces to that of Cil et al. (1998) when gravity is neglected and the wettability factor is $\cos\theta$. Lee and Kang (1999) have carried out water injection tests through artificially fractured samples of Berea sandstone that initially were saturated with oil to study the effect of variable fracture aperture in water injection. Testing of water injection into a fractured porous media has been considered by several other authors. Pooladi-Darvish and Firoozabadi, 2000a reported a wide range of water injection and spontaneous countercurrent imbibition experiments on water-wet fractured porous media. The governing time-dependent imbibition equation is a nonlinear diffusion-type equation in which the diffusion-like coefficient, D [m^2/s], is a function of water saturation. Therefore, they introduced the dimensionless time in the form

$$T=\frac{D(S_w)}{L^2}t \tag{9}$$

On the other hand, Behbahani (2004) tested some of the previously suggested nondimensional time when simulating imbibition recovery in water-wet media for various oil to water viscosity ratios, between 0.01and 200. His work shows that the time-scale for recovery in water-wet systems for finite viscosities is proportional to the geometric mean of the oil and water viscosities, as suggested by Ma et al. (1997).