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Analysis of counter-current spontaneous imbibition in presence of resistive gravity forces: Displacement characteristics and scaling

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ABSTRACT

Counter-current spontaneous imbibition (COUCSI) is an important mechanism of recovery from tight matrix blocks in naturally fractured reservoirs. In this study, by means of numerical simulation experiments we show that significant differences in terms of the final recovery and imbibition rate exist between COUCSI with and without the gravity forces. A specific situation where gravity forces are resisting the process is considered. For COUCSI in presence of these forces, literature on the scaling of recovery is limited. To present appropriate scaling equations, two approaches have been examined on the main governing equation; (1) inspectional analysis and (2) applying an approximate analytical solution. The scaling equations based on the latter approach give better results than those derived from the inspectional analysis and scaling equations in the literature, as well. The new scaling equations accounting for the resistive gravity forces and relative permeability and capillary pressure properties are presented, which are consistent with the common scaling situations, as well.

Introduction

In naturally fractured reservoirs imbibition process, i.e., displacing the nonwetting phase (either oil or gas) by wetting phase, is an important mechanism for oil and gas recovery from tight matrix blocks during many processes. In this work, a specific form of the counter-current spontaneous imbibition (COUCSI) where capillary forces are the only driving forces and gravity forces are resisting the displacement is considered. For further information on the details of different situations that may occur, the readers are referred to Iffly et al. (1972), Schechter et al. (1994), Pooladi-Darvish and Firoozabadi (2000), Qasem et al. (2008), Bourbiaux (2009) and Mirzaei-Paiaman et al. (2011b).

The COUCSI with negligible gravity effects has been widely studied (Morrow and Mason, 2001; Mason and Morrow, 2013). In this case the process can be divided into two periods. The early time period, also called infinite acting, frontal flow, or pre-contact period, occurs as if into a semi-infinite medium. This period occurs before the imbibition front reaches the no-flow boundary (NFB). During this period, which is responsible for most of the recovery, the recovery varies linearly by square root of time as reported by Handy (1960), Reis and Cil (1993), Chen et al. (1995), Cai et al. (2010, 2012), Schmid and Geiger (2012, 2013), Mirzaei-Paiaman and Masihi (2013, 2014) and Mirzaei-Paiaman et al. (2013). The second period is the late time period (also called finite acting, boundary dominated or post-contact period) and occurs if the imbibition front arrives at the NFB. In this period the recovery is an exponential function of time (Reis and Cil, 1993; Tavassoli et al., 2005). Each of these flow periods can be identified from recovery data by either plotting the imbibition rate versus time on a log–log scale (Chen et al., 1995; Cil et al., 1998) or plotting recovery versus square root of time. In the former, a straight line can be drawn through the data points for each flow period and the intersection point of the two straight lines reflects approximately the time at which the imbibition front hits the NFB. In the latter method a straight line can be fitted to the data points only for infinite acting period. The point at which data points start to deviate from the fitted straight line represents approximately the beginning of the finite acting period.

For the COUCSI when gravity effects are absent numerous scaling equations exist (Schmid and Geiger, 2012, 2013; Mirzaei-Paiaman and Masihi, 2013). Recently, Schmid and Geiger (2012, 2013) and Mirzaei-Paiaman and Masihi (2013) presented universal scaling equations for the infinite acting period of the COUCSI in the absence of gravity forces. However, as will be presented later in this work, the recovery performances with and without the gravity forces are different. Therefore, implementation of the scaling equations developed specifically for the infinite acting period of the zero gravity COUCSI to the whole process of the non-zero gravity COUCSI should be done with caution.

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Since there is no known exact analytical solution to the main governing equation in the presence of gravity forces, literature works use either the inspectional analysis or different approximate solutions (Xie and Morrow, 2000; Li and Horne, 2006; Standnes, 2010; Mirzaei-Paiaman et al., 2011a). Xie and Morrow (2000) proposed semi-empirically a scaling equation in the presence of driving gravity forces. Li and Horne (2006) used an approximate solution with the assumption of linear capillary pressure profile. By Lambert's W function, Standnes (2010) presented an equation on the basis of the single capillary tube model. Mirzaei-Paiaman et al. (2011a) utilized an approximate solution working with the weak or integral form of the corresponding partial differential governing equations presented earlier by Tavassoli et al. (2005) to develop a single scaling equation. The scaling equations given by Xie and Morrow (2000) and Standnes (2010) do not include the relative permeability and capillary pressure effects and are limited to the systems with the same wetting conditions. The scaling equation given by Standnes (2010) does not account for the gravity forces. The scaling equations by Xie and Morrow (2000), Li and Horne (2006), Standnes (2010) and Mirzaei-Paiaman et al. (2011a) do not consider the consistency between the vertical and horizontal axes in different scaling situations, as well, as highlighted by Mirzaei-Paiaman and Masihi (2013). Mirzaei-Paiaman and Masihi (2013) noticed that during development of any scaling equation consistency with common practices should be considered. A single scaling equation cannot be used in different scaling practices, and each scaling practice requires its corresponding scaling equation (Mirzaei-Paiaman and Masihi, 2013). The current scaling equations in the presence of the gravity forces along with the recently published exact scaling equations in the absence of gravity forces by Mirzaei-Paiaman and Masihi (2013) for one dimensional displacement are summarized in Table 1. Included parameters will be explained later within the text.

In the scaling part of this study we first consider the inspectional analysis of the main governing equation of the COUCSI in the presence of gravity forces to investigate limitations of this approach. Because of many simplifying assumptions and the nature of such method the scaling equation derived using this method is not accurate in scaling of the recovery data. We then utilize an approximate analytical solution to the problem (Tavassoli et al., 2005; Mirzaei-Paiaman et al., 2011a) to find the appropriate scaling equations. In the second approach, we consider the gravity forces, relative permeability and capillary pressure properties. In addition, the consistency between development of the new scaling equations and common scaling practices, as emphasized by Mirzaei-Paiaman and Masihi (2013) is considered. To investigate scaling ability of different scaling equations, we use the recovery data obtained from numerical simulation experiments. The reason for using the numerical simulation technique is that simulation of non-zero gravity cases in laboratory due to the need for the tall matrix blocks is often not practical.

The remaining portion of this paper is structured as follows. In Mathematical formulations Section we review the basic governing equation and an approximate analytical solution to the COUCSI process in the presence of resisting gravity effects (Tavassoli et al., 2005; Mirzaei-Paiaman et al., 2011a), followed by a brief introduction into the recently published universal scaling equations for the infinite acting period of the COUCSI in small size systems (Schmid and Geiger, 2012, 2013; Mirzaei-Paiaman and Masihi, 2013). Then, in Results and discussion Section the numerical solution to the main governing equation is presented and using a set of numerical simulation experiments, the recovery performance and existing flow periods/regimes in the subject systems are investigated. Then the inspectional analysis of the main governing equation and an approximate analytical solution to the problem is used to derive appropriate scaling equations. Finally, using several diverse recovery data generated by numerical simulation technique we check the ability of the different scaling equations derived on the basis of the two aforementioned methods and existing scaling equations in the literature.

Table 1
The current scaling equations in the presence of gravity forces. The recent universal scaling equations for the small size systems by Mirzaei-Paiaman and Masihi (2013) have also been included.

Work	Gravity presence	Methodology	Scaling equation	Limitations
Xie and Morrow (2000)	Yes	Semi-empirical	$t_{D,XM} = \left(\frac{\sigma\sqrt{\frac{k}{\phi}}}{\sqrt{\mu_w\mu_{nw}}L^2} + \Delta\rho g H\right)t$	• Does not include the relative permeability and capillary pressure effects • Not consistent to the common scaling situations • No clear theoretical basis
Li and Horne (2006)	Yes	Approximate analytical solution to the main governing equation (linear capillary pressure profile)	$t_{D,LH=4\alpha R^2 t}$	• Not consistent to the common scaling situations
Standnes (2010)	Yes	Single capillary tube model	$t_{D,S} = 1 + W\left(-\exp\left(-1-\left(\frac{\sigma\sqrt{\frac{k}{2\phi}}}{\sqrt{\mu_w\mu_{nw}}L^2}\right)t\right)\right)$	• Does not include the gravity effects • Does not include the relative permeability and capillary pressure effects • Not consistent to the common scaling situations
Mirzaei-Paiaman et al. (2011a)	Yes	Approximate analytical solution to the main governing equation (Tavassoli et al., 2005)	$t_{D,MMS=\alpha R^2 t}$	• Not consistent to the common scaling situations
Mirzaei-Paiaman and Masihi (2013)	No	Exact analytical solution to the main governing equation (Schmid et al., 2011; Schmid and Geiger, 2012, 2013)	$t_{D,MP} = \frac{2AF'(S_{wi})}{\phi L_c}t^{1/2}$ $t_{D,MP\,V_p} = \frac{2A}{\phi L_c}t^{1/2}$ $t_{D,MP\,V_i} = \frac{2A}{\phi L_c(1-S_{wi})}t^{1/2}$	• Does not include the gravity effects
This study	Yes	Approximate analytical solution to the main governing equation (weak or integral form)	$t_{D,new} = 1 + W(-e^{-1-6\alpha R^2 t})$ $t_{D,new\,V_p} = \frac{(1-S_{nwr}-S_{wi})}{R}[1 + W(-e^{-1-6\alpha R^2 t})]$ $t_{D,new\,V_i} = \frac{(1-S_{nwr}-S_{wi})}{R(1-S_{wi})}[1 + W(-e^{-1-6\alpha R^2 t})]$	-