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Full Length Article

Scaling one- and multi-dimensional co-current spontaneous imbibition processes in fractured reservoirs

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ABSTRACT

Spontaneous Imbibition (SI) is in particular a very important mechanism for oil and gas recovery from matrix blocks in naturally fractured reservoirs. An analytical solution to the one-dimensional co-current spontaneous imbibition (COCSI) problem was proposed by Schmid et al. (2011). On the basis of this analytical solution, a set of scaling equations as well as a simplified one were developed for the COCSI process (Mirzaei-Paiaman and Masihi, 2014). The objective of this study was to validate these scaling equations using 12 one-dimensional COCSI experiments. To accommodate for multi-dimensionality of the COCSI process, a shape factor was proposed and incorporated into the one-dimensional scaling equations to make them applicable for any matrix size, shape and boundary conditions. The resulted scaling equations were validated through the use of data associated with 17 multi-dimensional water-oil COCSI experiments. The necessity of accounting for matrix anisotropy in the proposed scaling equations was also investigated.

1. Introduction

Spontaneous Imbibition (SI) of the wetting phase (WP) into the matrix blocks due to capillary forces is an important mechanism for recovery of oil/gas as the non-wetting phase (NWP) in naturally fractured reservoirs [39,46,47,32,28,34]. When other external drives (i.e. gravity or viscous forces) are negligible, the boundary conditions control the type of displacement to be either counter-current spontaneous imbibition (COUCSI) or co-current spontaneous imbibition (COCSI) [45]. The COUCSI process takes place when all the permeable surfaces of a NWP-saturated rock are brought into contact with the WP. The COCSI on the other hand occurs when only a portion of the permeable surfaces of the NWP-saturated rock is in contact with the WP and the remaining permeable surfaces are covered by the NWP. These two pore-scale processes are schematically presented in Fig. 1 for some unit control volumes associated with a sample pore structure by highlighting the flow directions and fluid phase distributions along the boundary lines.

It has been shown that COCSI is more efficient than COUCSI in terms of both final recovery and displacement rate [19,6,20,41,42,49,22,21,14,35,4]. The use of scaling equations proposed based on COUCSI experiments for the COCSI process leads to pessimistic forecasts regarding rate of recovery as well as final recovery values. It has been shown in the literature that the scaling equations developed for the COUCSI process fail to scale the COCSI data [20,2,24,49,40,14,33].

The existing scaling equations for the COCSI process only consider one-dimensional displacement. Under the one-dimensional COCSI process, the WP enters one end of a linear system and expels the NWP from the opposite end [43,25,23,5,44,33]. The analysis proposed by Rapoport [43] was based on simple inspectional analysis of the governing equations which suffers from many limitations [46,47,32,33]. The analyses proposed by Li and Horne [25], Li [23] and Bourbiaux [5] were based on some restricting assumptions such as presence of piston-like displacement as well as linear capillary pressure profile along the displacement path. The scaling equations proposed by Saboorian-Jooybari and Khademi [44] were limited to some specific functional forms of relative permeability and capillary pressure data. Based on the work by Schmid et al. [48], Mirzaei-Paiaman and Masihi [33] proposed scaling equations for one-dimensional COCSI. These equations assume that imbibition recovery varies linearly by square root of time [37,38]. There

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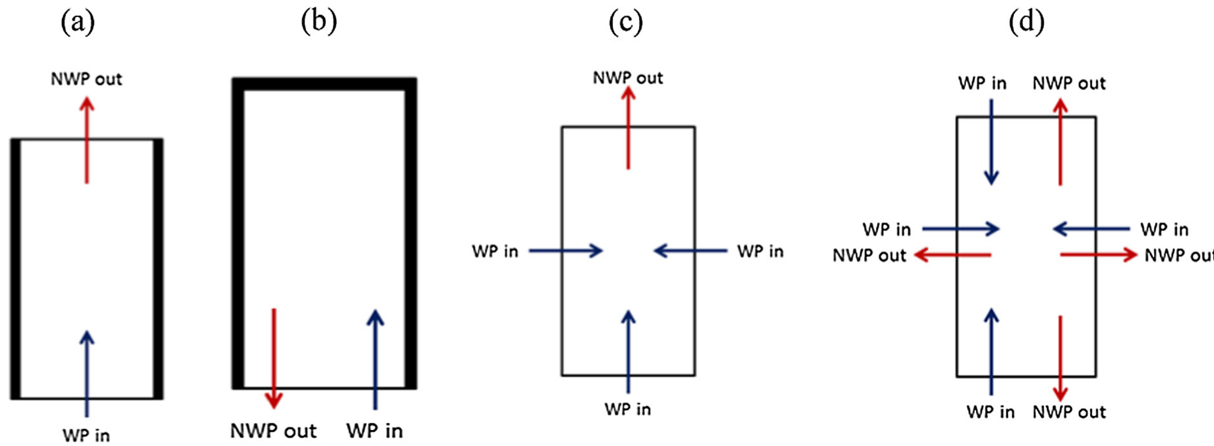

Fig. 1. Schematic representation of some COCSI and COUCSI tests. (a) One-dimensional COCSI, (b) one-dimensional COUCSI, (c) multi-dimensional COCSI and (d) multi-dimensional COUCSI.

exists cases that spontaneous imbibition recovery does not follow the classical square root of time law [18,17,9,50]. For the systems where COCSI recovery varies linearly by square root of time, the scaling equations proposed by Mirzaei-Paiaman and Masihi [33] incorporate all factors influencing the pure one-dimensional COCSI process. These equations were then used to extract a simple scaling equation free of capillary pressure and relative permeability functions which is applicable for some routine applications when these data are not available [33]. These scaling equations were then validated using limited number of one-dimensional COCSI experiments obtained from open literature, and satisfactory results were obtained.

As stated before, the scaling equations proposed by Mirzaei-Paiaman and Masihi [33] for one-dimensional COCSI process were obtained based on the analytical solution to pure one-dimensional COCSI problem proposed by Schmid et al. [48]. In a pure one-dimensional COCSI process, the WP enters the porous medium at a surface completely covered by the WP while the NWP leaves the porous medium at a surface completely covered by the NWP. In other words, there is no counter-current production of the NWP at the surface in contact with the WP. In practice, such a pure COCSI process does not exist and there is minor backflow production of the NWP at the face covered by the WP [6,7,8,41,42,24,49,15,10].

In multi-dimensional COCSI process, flow of the WP occurs in more than one direction. In an anisotropic medium in which directional permeability exists, the capillary pressure and relative permeability functions are also expected to depend on the flow direction. Now the question is how an anisotropic medium should be treated when is subjected to multi-dimensional COCSI process? Heinemann and Mittermeir [16] showed that the effect of different permeabilities in an anisotropic medium can be accounted for by incorporation of these different direction-dependent permeabilities in the context of a shape factor. Mirzaei-Paiaman and Masihi [32] proposed a definition for characteristic permeability to account for directionally-dependent permeability in an anisotropic porous medium. However, there has not been a solid solution to account for the effect of directionally-dependent capillary pressure and relative permeability functions on scaling the multi-dimensional COCSI process. In the absence of such a solution, the capillary pressure and relative permeability data, measured experimentally in one direction of flow in the lab, would be used to solve/scale the multi-dimensional COCSI process, even in anisotropic porous media.

To use the one-dimensional COCSI scaling equations for the multi-dimensional COCSI process, a shape factor (or a characteristic length) should be defined to account for different matrix shapes, sizes and boundary conditions. There is not any known generalized shape factor in the literature that can be used for the case of multi-dimensional COCSI process [49,33]. This shape factor can be defined based on the physical considerations and physics of the problem.

The first objective of this study is to validate the scaling equations, proposed by Mirzaei-Paiaman and Masihi [33] for one-dimensional COCSI process, using experimental data. This will enable us to check their validity for the real-case COCSI processes in which some NWP is also recovered counter-currently; however its share in the overall production of the NWP is not usually determined because of some technical and measurement difficulties. The second objective of this work is to validate the simplified scaling equation of Mirzaei-Paiaman and Masihi [33] for one-dimensional COCSI process using more experiment data. To accomplish the first and second objectives, twelve one-dimensional water-oil COCSI tests with variable WP viscosity and different porous media are used [13]. The third objective of this research is to extend the existing scaling equation proposed by Mirzaei-Paiaman and Masihi [33] to be applied for the case of multi-dimensional COCSI process by defining appropriate general shape factors or characteristic lengths. The forth objective of this research is to examine whether capillary pressure and relative permeability data, measured in the lab in one flow direction in an anisotropic porous medium, can be reasonably used for the purpose of solving/scaling the multi-dimensional COCSI process. To accomplish the third and fourth objectives, twelve multi-dimensional water-oil COCSI experiments were borrowed from the literature which were conducted using different WP viscosity as well as porous media types [13]. In addition to these experiments, five multi-dimensional water-oil COCSI tests on chalk, reported by Standnes [49], were also used.

2. The scaling equations for the COCSI process proposed by Mirzaei-Paiaman and Masihi [33]

The scaling equations for one-dimensional pure COCSI process in which there is zero counter-current production of oil at the boundary open to the WP are given below:

$$t_D = \frac{2AF'(S_{wi})}{\phi L} t^{1/2} \tag{1}$$