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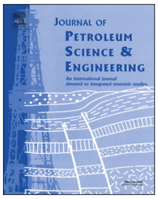

Estimation of pseudo relative permeability curves for a heterogeneous reservoir with a new automatic history matching algorithm

Amir Fayazi [a,b], Hadi Bagherzadeh [a], Abbas Shahrabadi [a,*]

[a] *EOR Research Department, Research Institute of Petroleum Industry (RIPI), Tehran, Iran*
[b] *Department of Chemical and Petroleum Engineering, Schulich School of Engineering, University of Calgary, 2500 University Drive NW, Calgary, AB, Canada T2N1N4*

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ABSTRACT

Reliable relative permeability curves are important for successful reservoir simulation and modeling. These curves may be available on fine scale models. However, detailed descriptions demand a huge amount of memory and processing time. Therefore, it is needed to upscale core-size relative permeability curves measured by laboratory experiments to a scale suitable for the various types of simulation. This upscaling is accomplished with pseudo functions. In this work, a new automatic history matching algorithm based on B-spline representation was applied to estimate pseudo relative permeability curves. The performance of the generated pseudo curves were compared with four dynamic pseudo functions for a 3D heterogeneous water-flooding case. In addition, the effect of the pseudo function estimation uncertainty on the cumulative oil production was investigated after 10 years of production. Results revealed that relative permeability curves obtained from history matching gives the best performance among other pseudos and this methodology can be used for reservoir simulation over periods beyond that of the original match.

1. Introduction

In numerical reservoir simulation, relative permeability curves are extremely important for reservoir evaluations because of their ability to predict fluid production during reservoir exploitation (Wang et al., 2009). Yet, ironically, relative permeability is perhaps the least understood and least accurately known property. Fortunately, it is not necessary to understand the physical or chemical mechanisms involved to use the concept. The only requirement is that good relative permeability data be available. Therefore, the problem is in obtaining good data on representative cores and upscaling that data to the rest of the reservoir (Trujillo, 1982).

In reservoir simulation, initially, estimates of relative permeability curves, commonly referred to as rock curves, are determined for a filed by laboratory measurements on core plugs (Al-Otaibi and Al-Majed, 1998; Malik and Lake, 1997). In theory, one could construct a reservoir model on the core-plug scale for accurate prediction of reservoir behavior (Kumar et al., 1997). However, the simulation of these models with great details and high grid definition is generally not practical because of the excessive computer time and memory that would be required, even with super computers and parallel computing technology (Fischbuch and Wattenbarger, 1991; Wang et al., 2009). Therefore, the detailed information must be incorporated into a coarser and less complex, fluid flow simulation model by means of some upscaling techniques. In general, upscaling means the determination of a coarser grid model with similar geometry of the fine grid model, which gives the same dynamic flow response when exposed to the identical boundary conditions (Hashemi et al., 2014). To construct these simple models, it is required to design a multi-step upscaling process to upscale from core-plug sized grid blocks to full-field simulation size grid blocks. If rock curves are used for simulation with coarse grid blocks, the important effects of heterogeneity will be omitted. Large simulation grid blocks will also cause large numerical dispersion (Azoug and Tiab, 2003). Therefore, these rock curves should be modified to account for the mathematical shortcomings of numerical simulation. This upscaling can be accomplished with pseudo functions or pseudo relative permeabilities that are the main goal of this research.

Pseudo functions (or pseudos) are tables of numbers, which allow reproducing fine grid results using the typical coarse grids of field simulations. Several pseudo function techniques have been proposed in recent decades (Barker and Dupouy, 1996; Barker and Thibeau, 1997). The properties and limitations of different pseudo function methods were reviewed by Barker and Thibeau (1997). It should be noted that the pseudoization approaches have the limitation that one must either be able to run the fine grid, or

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[*] Corresponding author.
E-mail address: shahrabadia@ripi.ir (A. Shahrabadi).

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Nomenclature

C	control point
d_f	fine grid center depth
D_c	coarse grid center depth
f	fractional flow
h	thickness
J	objective function
k_r	relative permeability
k_r^0	end point relative permeability
N	basis function
P	pressure
q	flow rate
S	saturation
T	transmissibility
V	pore volume

Greek letters

ρ	density
ϕ	porosity
μ	viscosity

select a representative section of the fine grid and assert that the pseudo functions are appropriate for use elsewhere in the model.

The pseudo functions were first introduced to the petroleum industry by Coats et al. (1967). They developed an analytical method to calculate pseudo relative permeability curves based on the assumption of gravity-capillary equilibrium in the vertical direction (vertical equilibrium). Jacks et al. (1973) introduced dynamic pseudos, which are applicable over a wide range of flow rates. Archer and Wong (1973) used a trial and error approach (manual history matching) to estimate pseudo relative permeability curves by history matching laboratory core flood data and Sigmund and McCaffery (1979) used non-linear regression for the same purpose. However, both authors estimated only the two parameters defining the shape of power law relative permeability curves. Later, splines were applied to obtain a more general representation of relative permeability curves (Kerig and Watson, 1986; Watson et al., 1988).

In 1979, Killough and Foster (1979) used vertical equilibrium pseudo relative permeabilities and pseudo capillary pressures in a three layered model to match the results from a 22-layered model of a portion of the Empire Abo field. They showed that the results of the two models were almost identical in both history matching and prediction phases. Johnson et al. (1982) generated pseudo relative permeabilities using a non-linear regression approach for full-field modeling of the Kuparuk River field. They found out that excellent match of the finely gridded model results could be obtained with an extremely coarse gridded model for both water-flood and reinjected gas displacement cases. Tan (1995) generated pseudo relative permeability curves with non-linear regression analysis to represent a fine 3D model with a coarse 3D model. They also checked the sensitivity of the pseudos to coarse grid definition and production rates. Guzman et al. (1994) discussed a number of dynamic pseudo methods and point out some of the problems associated with use of those methods. In 2009, Wang et al. (2009) developed a relative permeability upscaling technique for the coarse scale modeling of heterogeneous reservoirs. They applied single phase upscaling at the beginning to set up the base case for optimization and conducted the regression runs by non-linear optimization.

Despite the extensive research that has been performed in the past few decades, effective upscaling to preserve the fine scale simulation results in heterogeneous reservoirs still remains a challenging procedure. In this work a new automatic history matching algorithm based on B-spline representation was applied to estimate pseudo relative permeability curves. The performance of the pseudo curves obtained from reservoir performance history data are compared with dynamic pseudo functions (Kyte and Berry, Pore Volume Weighted, Transmissibility Weighted, and Stone Methods) for a 3D heterogeneous water-flooding case.

2. Dynamic pseudo functions

Numerous dynamic pseudo function generation methods have been published in literature. Basically, there are three kinds of dynamic pseudo functions which are presented in Table 1 (Azoug and Tiab, 2003). In the followings, the equations for pseudo functions of Kyte and Berry, Pore Volume Weighted, Transmissibility Weighted, and Stone are presented briefly. It should be mentioned that pore volume weighted average is used in these methods for calculating the coarse grid density, viscosity and saturation. In addition, volume weighted average is used for calculating the coarse grid porosity and a combination of harmonic and arithmetic average is used for calculating the coarse grid permeability.

2.1. Kyte and Berry (KB)

Kyte and Berry introduced a method for controlling of numerical dispersion in coarse grid simulation. This method is based on upscaled pressures which are calculated as a $k_{rl}kh$ weighted average over the central plane of the fine grid cells, normal to the flow direction. Each phase pressure in the fine grid is first referenced to a datum position at the depth of the coarse grid center point (e.g. in x direction).

$$\bar{P}_l = \frac{\sum_k \sum_j \left[k_{rl}kh\left(P_l + \rho_l g\left(D_c - d_f\right)\right)\right]_{jk}}{\sum_k \sum_j \left(k_{rl}kh\right)_{jk}} \qquad l = o, w \tag{1}$$

Table 1
Different kinds of dynamic pseudo functions.

Pseudo function	Description	Example
Individual phase flow rate pseudo function	They are based on the upscaled Darcy's law to match each fine grid phase flow rate with the corresponding coarse grid flow rate directly.	Jacks et al. (1973) Kyte and Berry (1975) Pore Volume Weighted method
Average total mobility based pseudo function	They are based on an average total mobility and they try to fit the coarse and fine grid pressure or potential gradients.	Stone (1991) Hewett and Behrens (1991)
Streamline Method	They are based on the use of streamtubes derived from a single-phase fine grid simulation.	Hewett and Yamada (1997)