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A method for evaluation of water flooding performance in fractured reservoirs

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ABSTRACT

A mathematical model is developed for evaluation of water flooding performance in a highly fractured reservoir. The model transforms a dual-porosity medium into an equivalent single porosity medium by using a pseudo relative permeability method to normalize the relative permeability. This approach allows both fractures and matrix to have permeability, porosity, endpoint saturation, and endpoint relative permeability by themselves. Imbibition is also taken into account by modifying Chen's equation. Some effects, including imbibition and recovery rates are investigated. The investigation shows that imbibition can determine the potential of a fractured reservoir and a low recovery rate can improve the water flooding situation in terms of retarding water breakthrough and controlling the rise of water cut. A new chart composed by water cut vs. recovery curves is protracted to estimate the ultimate water-flooding recovery rate. The water flooding performance of two reservoirs is evaluated. Compared with numerical simulation method, the error of these two cases are not more than 2%, which proved that this method is reliable. Both lab test data and field data are applied to a further discussion of the characteristics of water flooding performance in fractured reservoirs. On comparison with the classical method, such as Tong's method and the X-plot method, the reason why the new method is more suitable to fractured reservoirs is addressed by a theoretical analysis. An appropriate application of this method can help the reservoir engineer to optimize the reservoir management with low costs and high efficiency.

1. Introduction

Experiences from oil recovery around the globe have shown distinct water flooding performance in fractured reservoirs than in conventional reservoirs. In most cases, the recovery usually begins with a high production rate in an early stage and then declines dramatically once water breaks through due to a rapid rise in water cut, especially in some high yield wells. Moreover, the geological complexity is also a barrier for accurate estimation of the water flooding performance and the potential of a fractured reservoir. Furthermore, as everyone knows, it is significant to perform reservoir management and investment decision.

For interpretation of water flooding performance in fractured reservoirs, many research papers have been published. Currently used methods can be classified as two categories: reservoir simulation and a reservoir performance analysis. The reservoir simulation methods consist of numerical simulation and physical simulation. Models of dual-porosity (Barenblatt et al., 1960) and shape factors (Warren and Root, 1963; Kazemi et al., 1976) are widely used in numerical simulation of the fractured reservoirs. But one of the main problems is that these models are over-simplified to meet the demand of computing. Another problem is that history matching is a subjective process. That is, various results may be obtained on the basis of the same data. Because of more tunable parameters in a dual-porosity model, more probable choices may be made by reservoir engineers. Some new technologies, such as a discrete fracture network (DFN) model and unstructured grids (Hoteit and Firoozabadi, 2008a, 2008b; Huang et al., 2011), can characterize a fracture network more accurately. However, technical limitation on information collection of in-situ fractures and enormous amount of computing are impediments to their application. Actually, the physical simulation (Yuetian et al., 2013) provides an objective way to present the water flooding performance in fractured reservoirs, but high costs and low efficiency are bottleneck problems.

Compared with the reservoir simulation methods, the reservoir performance analysis methods are easy, fast and cheap tools, which are composed of analytical models, empirical models and semi-empirical models. But these types of methods need more field data

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Nomenclature

A	coefficient, dimensionless
B	coefficient, dimensionless
b	fracture aperture [L], m
f_w	water cut, dimensionless
$f/\ wf$	the derivative of water cut of fracture, dimensionless
h	formation thickness [L], m
k_f, k_{ff}	conventional/intrinsic fracture permeability $[L]^2$, μm
k_m	matrix permeability $[L]^2$, μm
k_T	total permeability $[L]^2$, μm
k_{rof}, k_{rom}, k_{roT}	oil relative permeability in fracture/matrix/total, dimensionless
k_{rwf}, k_{rwm}, k_{rwT}	water relative permeability in fracture/matrix/total, dimensionless
L	length [L], m
$P1$–$P27$	coefficient, dimensionless
Q_o	cumulative oil, dimensionless
q_{imb}	imbibition rate, dimensionless
q_{wf}, q_{wm}, q_{wT}	fracture/matrix/total flow rate $[L]^2[T]^{-1}$, m^2/s
R	recovery factor of OOIP, dimensionless
R'	ultimate recovery factor, dimensionless
R^*	recovery in normalized range, dimensionless
R_f, R_m, R_T	fracture/matrix/total recovery factor of OOIP, dimensionless
R'_f, R'_m, R'_T	fracture/matrix/total ultimate recovery factor, dimensionless
S_{wf}, S_{wm}, S_{wT}	water saturation of fracture/matrix/total, dimensionless
S_{of}, S_{om}, S_{oT}	oil saturation in fracture/matrix/total, dimensionless
S_{orf}, S_{orm}, S_{orT}	residual oil saturation in fracture/matrix/total, dimensionless
S_{wif}, S_{wim}, S_{wiT}	initial water saturation in fracture/matrix/total, dimensionless
S^*_{wef}, S^*_{wem}, S^*_{weT}	fracture/matrix/total water saturation at outflow end in normalized range, dimensionless
S^A_{wf}, S^A_{wm}, S^A_{wT}	average water saturation in fracture/matrix/total, dimensionless
S^{*A}_{wT}	fracture average water saturation in normalized range, dimensionless
S^{*A}_{wBT}	water saturation at breakthrough time in normalized range, dimensionless
t	time [T], s
t_B	water breakthrough time [T], s
V_{wf}, V_{wm}, V_{wT}	fracture/matrix/total water volume $[L]^3$, m^3
W	recovery rate [L] $[T]^{-1}$, m/s
X	length [L], m
μ_o, μ_w	oil viscosity $[M][L]^{-1}[T]$, Pa s
ϕ_f, ϕ_m	fracture/matrix porosity, dimensionless
λ	imbibition index, dimensionless

and recovery experience to develop, and the predicting results also need more checks with field production. The theory of Buckley and Leverett (1942) and the Welge (1952) equation were first proposed to explain the phenomena of two-phase flow in reservoirs. According to experiments of Efros (1958), a relationship between oil cut, oil viscosity and outflow end water saturation in a process of water–oil displacement was obtained. Timmerman (1971) found a relationship between cumulative oil production and an oil–water ratio (i.e., $(1-f_w)/f_w$) by field data, which was from a water flooding reservoir in Illinois. Tong (1978, 1988) studied statistical data from more than 20 water flooding reservoirs around the globe and drew a chart for engineers to evaluate the water flooding performance. Chen (1985) deduced some water displacement curve(WDC) methods by using the theory of Buckley–Leverett, the Welge equation and the relation found by Efros, and the results were consistent with Tong's survey. As more advances in the technology of reservoir water flooding evaluation are made, more types of reservoirs have been put into consideration by researchers. El-khatib (2001, 2012) applied the Buckley–Leverett displacement theory to study water flooding in non-communicating stratified reservoirs and in inclined communicating stratified reservoirs. Yang (2009) proposed a new diagnostic analysis method for water flooding performance in conventional reservoirs.

In fact, many lessons and much experience have already been learned from hundreds of fractured reservoirs (Allan and Sun, 2003; Sun and Sloan, 2003) during past many years (Dang et al., 2011). Many researchers have published many mathematical models to interpret multi-phase flow in fractured medium, such as the De Swaan (1978) model, the Kazemi analytical model (1992) and the Civan (1998) model. However, the existing problems of evaluating water flooding performance in fractured reservoirs have not been figured out properly. One of the critical problems is how to deal with oil–water flow in a dual-porosity medium. Another issue is how to detect the influence of imbibition on the in-situ flow and the performance of oil wells. This paper aims to solve the above mentioned problems. First, a model is proposed for water–oil flow in a matrix-fracture medium by using the method of pseudo relative permeability curves. Then Chen's model (1982) is modified for calculation of the water breakthrough time and water saturation at the breakthrough time. A chart is composed for water-flooding evaluation by estimation of the ultimate recovery factor. Then the water flooding performance in two fractured reservoirs is evaluated. Compared with the classical method, such as Tong's chart and X-plot method (1978), some analyses are conducted and influential factors are discussed.

2. Mathematical model

2.1. Assumptions and definitions

A well group consists of one injector and one producer in a highly fractured reservoir, and the Kazemi modeling concept (1976) is used, as shown in Fig. 1. The additional assumptions are given as follows: the flow is linear, isothermal, and incompressible, and it obeys Darcy's law; in a dual-porosity model, fracture and matrix have its own irreducible water saturation, permeability, porosity and relativity permeability; the water–oil displacement in this case is non-piston-like; finally, the reservoir is water-wet and the imbibition effect is taken into account.

2.2. Pseudo relative permeability

Hearn (1971) used the pseudo relative permeability method to simulate a stratified reservoir by water flooding, which means that the reservoir is divided into many layers. Babadagli and Ershaghi (1993) introduced this method into the dual porosity concept and proposed the effective fracture relative permeability (EFRP) method to reduce the model to a single porosity fracture network model. In the stratified reservoir, each layer has its own thickness, porosity, initial water saturation, and residual oil saturation. Similarly, in a fractured reservoir, either fractures or matrix has