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Research paper

Numerical modeling of hyperbolic dominant transient fluid flow in saturated fractured rocks using Darcian approach

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ABSTRACT

A numerical model has been developed for simulating fluid flow in a coupled fracture-matrix system by considering a hyperbolic dominant fluid flow equation within the fracture as against the conventional parabolic dominant fluid flow equation. In addition, for the first time a transient fluid mass transfer function has been introduced in the governing equation of fluid flow within the rock-matrix in order to explicitly consider the fluid drainage from rock-matrix into the fracture. The effectiveness in modeling fluid flow using different governing equations developed by implementing the pseudo-steady state and transient models of transfer functions with parabolic and hyperbolic conditions within the fracture and rock-matrix has been discussed in detail. Numerical results suggest that the drainage of fluid from the rock-matrix to the fracture and thus the estimation of its fluid recovery from the reservoir are overestimated in a typical coupled fracture-matrix system using conventional parabolic dominant fluid flow equation. It has been further observed that among the hyperbolic and parabolic dominant mathematical models used to describe the fluid flow through fracture, the recent model proposed by the first author, which is associated with the rate limited fluid mass transfer term within the low permeable rock-matrix yields a significantly varying pressure distribution with reference to the rest of the cases. It is also observed that the resultant pressure distribution within a coupled fracture-matrix system is independent of the pseudo-steady state transfer or transient transfer function, which is used for modeling the fluid interaction at the fracture-matrix interface.

1. Introduction

It is well known that the groundwater extraction from alluvial aquifers around the globe has made a significant contribution to the enhancement of the social and economic status of the mankind. However, such extraction from fractured aquifers remain limited due to the limited knowledge associated with characterizing a fractured aquifer. Apart from groundwater resources, it is also known that more than half of the world's proven oil reserves and a nearly half of the world's gas reserves are trapped in carbonate reservoirs that are naturally fractured. A sound understanding on fluid flow through rock fractures at the scale of a single fracture is fundamental in characterizing a network of complex fractured reservoir, which essentially dictates the production performance as well as the recovery of oil and gas. Thus, an improved knowledge associated with a fractured aquifer is imminent in the context of both groundwater sustainability as well as oil recovery. It can also be noted that the modeling of a complex fracture network on a three-dimensional scale not necessarily replicate the real reservoir dynamics as the resultant fluid flow through a connected network of fractures does not occur through all the naturally-connected or synthetically-generated fractures, while the fluid flow occurs through the limited preferential pathways dictated by the coupled hydro-geo-mechanical effects at a much larger scale than perceived by the conventional Representative Elementary Volume (Barrenblatt and Zheltov, 1960; Warren and Root, 1963; Adams et al., 1968; Najurieta, 1980; Nanba, 1991; Lim and Aziz, 1995; Sekhar et al., 2006; Suresh Kumar, 2008; Ortiz et al., 2013; Natarajan and Suresh Kumar, 2011; Natarajan and Suresh Kumar, 2012; Suresh Kumar, 2014a, 2014b, 2014c), thereby making the fluid dynamics associated with a saturated aquifer or a petroleum reservoir to be extremely complex. The petroleum reservoir or a geothermal reservoir fluid dynamics require the knowledge of thermodynamics as well, since the reservoir fluid flow is generally associated with high temperature and high pressure conditions involving phase changes. In essence, one requires solving a multi-phase, multi-component three-dimensional fluid flow equation in order to grasp the exact reservoir dynamics of a fractured reservoir. However, the focus of the present study is limited to a single-component, single-phase fluid flow through a fractured

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reservoir at the scale of a single fracture in a coupled fracture-matrix system using the concept of dual-continuum.

1.1. Fracture and rock-matrix fluid flow

As the fluid flow through saturated rock fractures has a direct influence on the economic production of crude oil as well as on the groundwater recharge potential in fractured rocks, the hydraulic behavior of fluid flow through a fractured reservoir plays a very critical role. The hydraulic behavior in turn determines the nature of governing fluid flow equations within the physical system. Fractured reservoir, in general is composed of two fundamental entities namely low permeable rock-matrix, where the oil or the groundwater has been stored, and a high permeable fracture, through which oil or groundwater is transmitted towards the production well. The fluid interaction at the fracture-matrix interface determines the quantum of oil or groundwater that will be drained from stored rock-matrix into high permeable fracture. Since, the porosity and permeability of fracture and rock-matrix vary over several orders of magnitudes, the assumption of single continuum in a fractured carbonate reservoir is highly idealistic. In this context, the physical domain of interest in the case of a fractured reservoir is split into two different continuums, one for fracture; and the other for rock-matrix; and the both the continuums are assumed to be connected effectively at the fracture-matrix interface. The rock-matrix despite being low permeable has the characteristic feature of a typical porous medium, and hence, the conventional parabolic dominant linear diffusivity equation can be applied comfortably. The mathematical nature of a parabolic equation typically implies that the physical system of interest will try to reach a steady-state condition after a sufficiently long time. Thus, it is reasonable to anticipate a steady-state condition within the rock-matrix after a long time as the initial perturbations or noises associated with the pressure distribution within the rock-matrix will eventually vanish with time. In this context, conventionally, the same parabolic dominant linear diffusivity equation is also applied to represent the fluid flow within the high permeable fracture. However, it is to be noted that the porosity of a single fracture pertains to 100% and also, the fluid flow through a single rock fracture resembles the fluid flow through a pipe. Since, the fluid velocity associated with the fracture is several orders of magnitude higher than that of the fluid velocity associated with the rock-matrix, the conventional assumption of parabolic dominant fluid flow within the high permeable fracture may not be always valid and needs a relook. In this context, a better description of fluid flow within the fracture associated with a fractured reservoir is very critical to the successful design and operation of petroleum reservoir projects and/or artificial groundwater recharge in fractured rocks.

To start with many researchers have developed models in order to investigate the mechanism of fluid flow and a relatively efficient method has been deduced to recover oil from fractured reservoirs. To mention a few, despite the discovery of the very first fractured reservoir in 1880 (Hubbert and Wills, 1955), Horner (1951) clearly pointed out that the conventional well-test analysis associated with a homogeneous saturated sub-surface reservoir cannot be extended in order to apply the same for a highly heterogeneous complex saturated fractured reservoir. In this context, Baker (1955) first ever tried to characterize a fractured reservoir with reference to its new fundamental entity called a "fracture". This new hydro-geological entity was associated with the earlier works by Lamb (1932), Muskat (1937), and Huitt (1956) in order to deduce an equation that describes the steady-state fluid flow through a typical fracture, which is in line with the earlier equations describing fluid flow through smooth parallel plates. Thus, Baker (1955) for the very first time modeled a steady-state fluid flow through a fracture as a function of width and depth of the fracture, in addition to the conventional consideration of the developed pressure gradient along the direction of fluid flow. Baker's (1955) being a steady-state model, Pollard (1959) for the first time modeled a transient fluid flow problem associated with a fractured reservoir. It should be noted here that until this point (1959), the earlier studies assumed that there was no fluid mass exchange between the so called fine non-communicating voids and coarse communicating voids. It was Barenblatt et al. (1960) who first considered a fractured reservoir that consists of two different porous media with two different pore sizes, where the very critical concept of fluid mass exchange between these two porous media was introduced. During the same period, Barenblatt et al. (1960) extended the fracture fluid flow analysis for a slightly compressible fluid as well. Since each porous medium represents a continuum, the model proposed by Barenblatt et al. (1960) was referred to as a "dual-continuum" model. The concept of "dual-continuum" essentially implies that in a geological formation with extremely varying porosity and permeability distributions (for example, in a fractured reservoir), it is nearly impossible to deduce a reasonable Representative Elementary Volume (REV) over which a mean value of variable such as intrinsic permeability can be deduced using the conventional single continuum approach. It can be noted that at the scale of a single fracture, the porosity of fracture corresponds to cent percent, while that of its adjacent rock-matrix can have porosity as low as 0.1% (three orders of variation in magnitude over a very small distance). Similarly, the permeability of fracture is in general several magnitudes higher than that of its associated rock-matrix permeability. Thus, a huge variation in magnitude over a very short distance yields steep gradient in flux distributions at the fracture-matrix interface; and this shock or discontinuity severely disturbs the continuity of fluid mass fluxes at the fracture-matrix interface; and it does not allow to make use of the conventional single-continuum concept comfortably as the fundamental assumption of smooth and continuous variation of dependent variable of interest (pressure in this case) in the physical domain is violated at the fracture-matrix interface. Hence, the associated fundamental geological units namely fracture and rock-matrix is treated as two different continuums connected by the diffusive limited fluid mass exchange term. Thus, in a typical dual-continuum model, the fluid flow equations are solved separately for both the continuums and the equations are coupled with a transfer term that characterizes the fluid mass transfer between the fracture and the rock-matrix (Warren and Root, 1963). Both the models by Warren and Root (1963) and Adams et al. (1968) projected a two straight line theory for the temporal variation of pressure associated with a fractured reservoir. However, it should be noted here that these plots were resulted from the variations of hydraulic head within a given fracture, which was expressed at the scale of a single fracture, while considering a pseudo-steady-state fluid mass transfer between low permeable rock-matrix and high permeable fracture. In other words, the transient nature of hydraulic head distribution within the low permeable rock-matrix was not considered explicitly, and instead, a pseudo-steady-state mass transfer function as a function of mean rock-matrix pressure was introduced at the fracture-matrix interface, in order to consider the drainage from the rock-matrix. Later, Kazemi (1969) numerically modeled the drainage from rock-matrix into fracture by considering the transient nature of hydraulic head distribution within the low permeable rock-matrix. As a result, the plot which provides the pressure as a function of logarithmic time yielded three distinct regions in describing the fluid flow through a fractured reservoir. The first slope represents the early stage fracture dominated fluid flow, while the intermediate nearly horizontal profile represents the transient fluid mass exchange between rock-matrix and fracture; and the final slope at the later stage represents the pseudo-steady state rock-matrix flow. Thus, the introduction of transient nature of hydraulic head distribution within the low-permeable rock-matrix helped to better characterize a fractured reservoir. In fact, a plenty of numerical and analytical studies have been conducted in modeling the fluid flow in fractured reservoirs in the past few decades. For example, Kazemi (1969) proposed a theoretical model for a naturally fractured reservoir based on the analytical model introduced by Warren and Root (1963). It was concluded that the pressure transient analysis of a naturally fractured reservoir depends on the degree and type of