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Significance of non-Darcy flow effect in fractured tight reservoirs

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A B S T R A C T

Reservoir development is increasingly moving towards unconventional resources such as tight reservoirs due to the rapid decline in conventional reserves. Several researches have been done in the petroleum industry addressing significant influence of non-Darcy flow behavior on well deliverability and reservoir performance. In all of the previous works, it is generally believed that the non-Darcy flow in a reservoir, if occurs, becomes considerable within a few feet around the wellbores beyond which it is negligible. Furthermore, wherever non-Darcy effect is mentioned in the literature, attention has usually been focused on gas wells with high production rates (i.e., rates higher than 10 *MMSCF/day*).

In this paper, correlations that are typically used for determination of non-Darcy coefficient are reviewed. Then, it is shown that the correlations are distinct and lead to considerably different values of the non-Darcy coefficient for the same rock sample. A simple guideline is also presented for choosing the most appropriate correlation for a reservoir. Main body of this paper is directed at accurate description of non-Darcy flow in fractured tight reservoirs. This study evaluates the validity of a widely accepted assumption, which considers non-Darcy effect significant only within a few feet around wellbore of gas wells producing at high rates. A synthetic simulation model is made using the data of a well from one of the Iranian fractured tight reservoirs. A full feature compositional simulator is used for the computations in this study. The distance out of the wellbore is subdivided into a number of regions, and then the necessity of including the non-Darcy component in each of the regions for better performance predictions is investigated. The effect of accounting the non-Darcy term in each of the regions on the simulation results such as production rate, final recovery and pressure behavior is studied. Furthermore, three distinct reservoir fluid types including dry gas, gas condensate and black oil are used with the objective well model to evaluate dependence of non-Darcy effect on the type of flowing fluid. The study results are used to provide guidelines about the necessity of global consideration of the non-Darcy term in simulation of different fluid systems even at low production rates. The results highlight that contribution of the non-Darcy component to flow can be significant even far away from wellbores, thus it must be considered globally in the bulk of reservoirs. Additionally, the study demonstrates that the role of non-Darcy component can be crucial even at low production rates regardless of reservoir fluid type. Therefore, in order to have accurate modeling, design and successful implementation of projects, simulations of fractured tight reservoirs must be performed with the global inclusion of the non-Darcy flow formulations regardless of the type of flowing stream and levels of production rate.

1. Introduction

Fluid flow through porous media is a key issue in many areas of the science such as petroleum engineering, groundwater hydrology, geothermal reservoirs and disposal of wastes into underground water (Saboorian-Jooybari and Khademi, 2014). Accurate modeling, design and successful implementation of projects in these areas are heavily dependent on the proper description of the flow behavior. In 1856, Henry Darcy developed his famous correlation to describe the dynamics of fluid flow in porous media as:

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Nomenclature

D	coefficient of rate-dependent skin, *day/MSCF*
d	characteristic length of a porous medium, *cm*
E	non-Darcy effect number, dimensionless
Fo	Forchheimer number, dimensionless
h	thickness, *ft*
k	absolute permeability, 10^{-15} m^2
M	molecular weight, *gr/mole*
P	pressure, *atm*
P_{sc}	pressure at standard condition, *psi*
q	gas production rate, *MMSCF/day*
Re	Reynolds number, dimensionless
r_w	wellbore radius, *ft*
s	constant skin factor, dimensionless
s'	total skin, dimensionless
T_{sc}	temperature at standard condition, $^{\circ}R$
v	superficial velocity, *cm/s*
x	direction of fluid flow, *cm*

Greek

ϕ	porosity, fraction
μ	dynamic viscosity, 10^{-3} *pa s*
μ_e	effective viscosity, 10^{-3} *pa s*
ρ	flowing fluid density, gr/cm^3
β	non-Darcy coefficient, cm^{-1}
τ	tortuosity, dimensionless
∂	partial derivative

Abbreviation

MMSCF/day	Million Standard Cubic Feet per Day
STB/day	Stock Tank Barrel per Day

$$-\frac{dP}{dx}=\frac{\mu v}{k} \tag{1}$$

where P is pressure, x is direction of fluid flow, μ is dynamic viscosity, v is superficial velocity, and k is absolute permeability. According to this equation, the pressure drop across a porous medium is linearly proportional to the fluid velocity. Later, experiments of Forchheimer (1901) revealed deviation from the linearity of Darcy's equation at high flow rates. They observed that at high flow rates the pressure drop exceeds that predicted by Darcy's law (Ergun, 1952). This phenomenon is called non-Darcy flow in the literature (Whitaker, 1996). Forchheimer added an additional pressure gradient proportional to the square of the velocity to represent the non-Darcy effect, and presented the following general fluid flow equation:

$$-\frac{dP}{dx}=\frac{\mu v}{k}+\beta\rho v^2 \tag{2}$$

where β is the non-Darcy coefficient and ρ is the flowing fluid density. The parameter β is also known with some other names. For example, it has been called the turbulence factor by Cornell and Katz (1953), the inertial coefficient by Ma and Ruth (1993a), the velocity coefficient by Firoozabadi and Katz (1979) and the inertial resistance coefficient by Geertsma (1974). In this paper, β is called the non-Darcy coefficient. Eq. (2) states that the total pressure gradient ($-dP/dx$) can be considered as the summation of the pressure gradients required to overcome viscous resistance ($\mu v/k$) and liquid–solid interactions ($\beta\rho v^2$).

Another extension to the Darcy's law is the Brinkman equation (1947), which was suggested for high permeable media,

$$-\frac{dP}{dx}=\frac{\mu v}{k}-\mu_e\frac{\partial^2 v}{\partial x^2} \tag{3}$$

where μ_e is the effective viscosity of the medium. This correction term takes into account the shearing effect at the confining walls. It is important to note that the Brinkman equation cannot be rigorously justified, except when the porosity is close to unity (Ingham and Pop, 2002), so it is not applicable to tight formations. Additionally, since the effective viscosity must be determined experimentally through sophisticated tests, thereby the equation is difficult to use and has not been implemented in commercial numerical simulators. Therefore, it is not discussed further here.

After Forchheimer, theoretical work of Hassanizadeh and Gray (1980) indicated that Darcy's law for describing the fluid flow through porous media is only valid for a limited range of velocities. The beginning of the non-Darcy flow is identified by two types of criteria: 1) the Reynolds number and 2) the Forchheimer number. Chilton and Colburn (1931) believed that non-Darcy flow through porous media is similar to turbulent flow in pipes, so non-Darcy flow can be identified by adopting the Reynolds number for turbulent flow in pipes:

$$\mathrm{Re}=\frac{\rho v d}{\mu} \tag{4}$$

where d is a characteristic length of the porous media. There is no consensus on the definition of such a length. For example, Chilton and Colburn (1931) and Ma and Ruth (1993b) respectively used the mean diameter of particles and pore throats as the characteristic length. Furthermore, the critical value of Re for the beginning of non-Darcy effect varies in a wide range of 0.01–100 in the works of different researchers (Andrade et al., 1998; Blick and Civan, 1988; Hassanizadeh and Gray, 1987). It is worth noting here that the application of the Reynolds number is only limited to unconsolidated or loosely-consolidated media for which a representative diameter can be determined. Due to the difficulty of determining the characteristic length, Green and Duwez (1951) modified the Reynolds number definition as below, which was later called the Forchheimer number (Fo) by Ma and Ruth (1993b).

$$Fo=\frac{k\beta\rho v}{\mu} \tag{5}$$

where k is absolute permeability. The Forchheimer number is the ratio of the pressure drop caused by the liquid–solid interaction ($\beta\rho v^2$) to that by the viscous resistance ($\mu v/k$). Although Fo has several advantages over Re including sound physical basis, clear definition and wide applicability to all kinds of porous media, it still suffers from the lack of agreement on the critical value for the beginning of the non-Darcy effect. Critical value of the Forchheimer number reported to vary in the range of 0.005–0.2 (Ma and Ruth, 1993b; Zeng and Grigg, 2006). Because of the inconsistency in definitions of the Reynolds and Forchheimer numbers, and thus their critical values, Zeng and Grigg (2006) presented the non-Darcy effect number using the definition of Forchheimer number,

$$E=\frac{Fo}{1+Fo} \tag{6}$$