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New technique for determining rate dependent skin factor & non-Darcy coefficient

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ABSTRACT

A non-Darcy flow develops in porous media when the velocity of reservoir fluids becomes extremely high because of the continuous narrowing of the cross section area of the flow and the convergence of flow streamlines. Therefore, the inertial effect increases significantly and the total pressure drop, required by fluids to move from the outer drainage area towards the wellbore increases significantly due to the extra pressure drop caused by the non-Darcy flow. The extra pressure drop is described by the Forchheimer equation in which the deviation from Darcy's law is proportional to the inertial factor which in turn is a function of porous media characteristics such as permeability and porosity.

This paper introduces a new technique for estimating rate dependent skin factors (DQ_{sc}) and non-Darcy flow coefficients (D). The new technique uses dimensionless pressure for steady state flow to determine these two parameters. A set of plots has been developed for the term (DQ_{sc}) based on reservoir configurations i.e. reservoir boundaries ($2x_e$ & $2y_e$), wellbore length, and anisotropy. All the plots have been developed based on the fact that the rate dependent skin factor represents the difference between the total pressure drop and the pressure drop caused by Darcy flow only when non-Darcy coefficient equals to zero. Dimensionless pressure drops for horizontal wells producing from finite acting reservoirs have been calculated for steady state flow when the impact of dimensionless time can be eliminated. The calculated pressure drops have been used in reservoir performance models to estimate rate dependent skin factors and non-Darcy coefficients.

A point of special interest in this study is the ability to estimate these two parameters without the need for experimental work or the need to use currently proposed empirical models for calculating them. This new technique requires knowing reservoir configurations (reservoir width and length), the length of the wellbore, and the height of the formation in addition to the anisotropy. The study indicates that rate dependent skin factors and non-Darcy coefficients have the minimum values when the reservoirs having square-shape drainage area. It has also been found that both parameters have great impact on wells with short wellbore length. Additionally, isotropic formations and symmetrical wells perform better than anisotropic formations and asymmetrical wells in terms of extra pressure drop caused by non-Darcy flow.

1. Introduction

Great attention has been given to non-Darcy flow beginning in the early 1900s when Forchheimer pointed out for the first time that Darcy's law is not applicable for high velocity gas flow in porous media without considering the inertial impact on pressure drop. For this reason, he stated that Darcy's law could be written in the following form (Forcheimer, 1901):

$$\frac{dP}{dr} = -\left[\frac{\mu}{k}v + \rho\beta v^2\right] \tag{1}$$

where (β) is the inertial factor which has numerous empirical models tabulated in the literature (Economides et al., 2013).

The pressure drop in gas reservoirs, caused by fluid flow, may have two trends: the first one is caused by Darcy flow when the velocity of reservoir fluid is low and the cross section area of flow is large enough for Darcy flow (Laminar flow approach) to be the dominant flow regime. The second is caused by non-Darcy flow when the cross section area of flow decreases gradually and flow streamlines come close together in such a way that the velocity increases to the turbulent condition limit. In this case, excessive pressure might be needed to overcome the inertial forces resulted from the convergence of flow streamlines. For horizontal wells, the extra pressure drop caused by non-Darcy flow, sometimes called choked flow, characterizes the flow regimes that typically result

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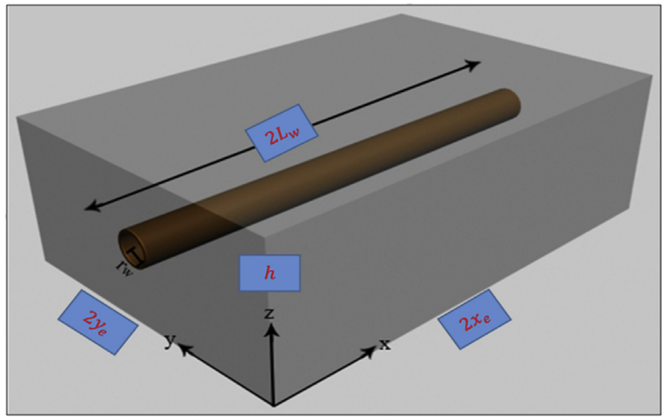

Fig. 1. Horizontal wellbore in bounded formation.

from change in the cross section area of flow and converging flow streamlines. This could happen for both early radial flow regimes observed during early production when reservoir fluids move radially in the vertical plane towards the wellbore or pseudo-radial flow regime, observed during late time production when reservoir fluids move radially in the horizontal plane towards the wellbore. However, it could happen also for linear flow regimes if the cross section area of flow is not large enough and therefore the developed velocity is so high that Darcy's law is no longer be applicable.

The non-Darcy flow accompanies pseudo-radial flow is characterized and controlled by reservoir boundaries and the horizontal permeability while the non-Darcy flow accompanies early radial flow is characterized and controlled by formation thickness and vertical permeability. Spivey et al. (2004) stated that more than 90% of the pressure drop within a distance of (0.5 *ft*) from wellbore could be caused by the non-Darcy flow developed by completion technique such as gravel-packed for vertical wells and slotted liner for horizontal wells. The non-Darcy flow coefficient for pseudo-radial flow when reservoir fluid flows in the outer drainage area and radially converges to the wellbore, is given by (Zeng and Zhao, 2008):

$$D = 2.22*10^{-15}\frac{\beta\gamma_g k}{h\mu}\left(\frac{1}{r_w}-\frac{1}{r_e}\right) \tag{2}$$

while the non-Darcy flow coefficient for early-radial flow near the wellbore, is given by:

$$D = 2.22*10^{-15}\frac{(\beta_s-\beta)\gamma_g k}{h\mu}\left(\frac{1}{r_w}-\frac{1}{r_s}\right) \tag{3}$$

where: (β) is the inertial factor at the outer drainage area of the reservoir and (β_s) is the inertial factor for the zone close to the wellbore or the damaged zone extended from the wellbore to radius of (r_s).

To characterize non-Darcy flow, the rate dependent skin factor (DQ_{sc}) should be determined. This term represents the dimensionless pressure drop and depends on the non-Darcy flow coefficient (D). Several models have been presented in the literature to estimate this coefficient. One of them was given by Ramey (1965):

$$D = 2.22*10^{-15}\frac{\beta\gamma_g k}{h\mu r_w} \tag{4}$$

It can be seen that the non-Darcy coefficient is a function of the petrophysical properties of the formation, such as permeability and porosity, inertial factor (β) which in turn is a function of permeability and porosity as well as reservoir fluid properties such as viscosity and specific gravity, in addition to the formation thickness and wellbore radius. A method of estimating the inertial factor has long been known from experimental studies (Barree and Conway, 2004, 2009). Based on these studies, several mathematical models have been proposed for this factor (Economides et al., 2013). Many researchers have suggested using gas well tests such as flow after flow tests, isochronal, and modified isochronal tests to predict the value of non-Darcy coefficient (Ramey, 1965), (Kelker, 2000), and (Brar and Aziz, 1978). Experimental studies have also been conducted to estimate non-Darcy coefficients especially for the pressure drop across the completion system (Nguyen, 1986).

Pressure drawdown and build up tests have also been used to determine the rate dependent skin factor (Zeng and Zhao, 2008). Spivey et al., 2004, suggested using sand face flow rate instead of surface gas flow rate for buildup test analysis to eliminate wellbore storage effects, while Kim and Kang, 1994, introduced a semi-analytical model for determining the non-Darcy flow coefficient from single rate gas well pressure transient tests. In this technique, pressure profiles and flow regimes could be derived from pressure and pressure derivative curves. Camacho-V et al., 1996, stated that pressure transient analysis could be used to characterize the non-Darcy coefficient and described it as the Reynold number. Therefore, well test analysis can be an excellent tool for characterizing these two parameters. However, the existence of different flow regimes, especially for horizontal wells, could cause some difficulties for estimating non-Darcy coefficient from well test analysis.

In this paper, the main focus will be on estimating rate dependent skin factors and non-Darcy flow coefficients using steady state pressure profiles and flow regimes. According to Matthews 1986 and Babu and Odeh 1989, the total pressure drop resulting from the depletion process of a horizontal well producing from finite acting reservoir could be separated into two terms. The first one represents the pseudo-steady state pressure drop that is a function of time and drainage area wherein reservoir pressure declines from its initial to average value. The second is the pressure drop at steady state when time does not have a significant impact on the pressure profile at any point in the reservoir. Therefore, dimensionless pressure can be simulated by several models and calculated for different reservoir configurations, horizontal wellbore lengths and anisotropy. Using the calculated dimensionless pressure, the rate dependent skin factor and non-Darcy flow coefficient can be determined.

1.1. Mathematical models for pressure profile

Consider a rectangular-shape formation with two side boundaries having the dimensions ($2x_e$ & $2y_e$) and height of (h) as shown