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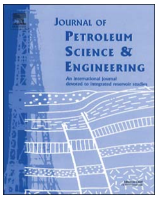

Decline curve analysis using rate normalized pseudo-cumulative function in a boundary dominated gas reservoir

Md. Shahin Alom*, Mohammad Tamim, Mohammed Mahbubur Rahman

Bangladesh University of Engineering & Technology, Dhaka, Bangladesh

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ABSTRACT

This paper presents a new and mathematically rigorous method to analyze declining gas production and pressure data using type curve. This method incorporates the pseudo parameters such as pseudo-cumulative production, real gas pseudopressure and a new pseudotime function for the first time to analyze rate-time curve.

The pseudotime function provides a convenient approach to handle variations in viscosity-compressibility values more rigorously with pressure since viscosity-compressibility ratio is a function of cumulative production.

The proposed method is based on the use of the new material balance pseudotime (T_a), called the rate normalized pseudo-cumulative function. A new algorithm is presented to compute the gas-in-place, and reservoir properties such as permeability, reservoir drainage area, and the pseudosteady sate constant.

This method is also capable to analyze the behavior of production data more rigorously for constant bottomhole pressure, variable rate/variable pressure drop, and strong depleted reservoir condition. The proposed method is a direct application of pseudosteady state relation that avoids iterations and extrapolation of data during analysis.

Finally, detail analysis and interpretation strategies are presented for both simulated and field data. The results obtained are in good agreement with previously reported results. The proposed method is strictly valid for boundary-dominated flow regime in gas reservoirs.

1. Introduction

Decline curve analysis (DCA) originally was the study of production behavior with time in order to predict future performance of a well. The early technique was developed by Arps. It was developed from empirical observations, and involved rate, time and cumulative production, but ignored the pressure data. This method provides future production rates and estimated ultimate recovery (EUR), but does not provide the original gas/oil in place or any reservoir properties. A lot of development has been done by various researchers since Arps. Modern techniques take into account the flowing pressure as well. Most importantly, these methods are not empirical, rather mathematically rigorous. These techniques involve different transformation of rate, pressure and time data, along with type curves. We may categorize decline analysis into two main streams- one involves rate versus time, and the other involves pressure versus time. The latter should fall under material balance method. Thus DCA nowadays is also called production data analysis (PDA). Modern PDA techniques are able to predict future rates, original oil/gas in place, and reservoir properties such as permeability, drainage area etc. In this regard PDA is comparable to traditional *pressure transient* analysis (PTA). To emphasize this point, PDA is also sometimes called *rate transient* analysis (RTA).

The first theoretical model was introduced by Fetkovich (1980) by combining pressure transient solution with Arps' empirical depletion model. This model assumed constant bottomhole flowing pressure, and introduced a type curve with dimensionless rate versus dimensionless time. The limitation imposed by constant bottomhole pressure was addressed by other researchers who introduced normalized rate (rate normalized by pressure drop) to account for the changing bottom hole pressure. Moreover, the concept of pseudo-time was introduced for gas reservoirs to handle the variation of gas properties that occurs due to changing pressures. Our work focused on gas reservoirs, thus the main objective was to test out the time functions. Fraim and Wattenbarger (1987) introduced real gas pseudopressure and normalized time approach, which is computationally intensive because it requires iterative techniques to compute average reservoir pressures. Blasingame and Lee (1988) introduced a mathematically rigorous method for analyzing variable-rate production data using material balance time function ($\bar{t}_a$), which is derived from cumulative production Gp., Palacio and Blasingame (1993) extended the work of Blasingame and Lee for decline

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* Corresponding author.
E-mail addresses: shahin.alom@mobilbd.com, sxalom@gmail.com (Md. S. Alom).

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Nomenclature

A	drainage area, ft^2
b	dclie curve exponentioal, dimentionless
B_g	gas formation volume factor, Rb/Mscf
B_{gi}	gas formation volume factor at initial reservoir pressure, RB/Mscf
C_A	reservoir shape factor, dimentinless
c_g	gas compessibility, psi^{-1}
c_{gi}	gas compessibility at initial reservoir pressure, psi^{-1}
c_t	total system compressibility, psi^{-1}
c_{ti}	total system compressibility at initial reservoir pressure, psi^{-1}
G	original gas-in-place, Mscf
G_P	cumulative gas production, Mscf
G_{pn}	pseudo-cumulative, Mscf
h	formation thickness, ft
k_g	effective permeability to gas, md
P	pressure, psia
$\overline{P}$	average reservoir pressure, psia
P_{sc}	pressure at standard condition, psia
P_D	dimensionless pressure response
P_i	initial reservoir pressure, psia
$m(P)$	Pseudopressure, psia
$m(P_i)$	normalized pseudopressure at initial reservoir pressure, psia
$m(P_i)_n$	normalized pseudopressure at initial reservoir pressure, psia
P_{wf}	bottomhole flowing pressure, psi
$m(P_{wf})_n$	normalized pseudopressure at bottomhole flowing pressure, psi
q	surface flow rate, Mscf/day
q_i	surface flow rate at initial reservoir pressure, Mscf/day
q_g	gas flow rate, Mscf/day
q_{gi}	gas flow rate at initial reservoir pressure, Mscf/day
q_D	dimensionless rate solutions
q_{Dd}	dimensionless decline rate
Q_n	normalized cumulative production
r_w	wellbore radius, ft
r'_w	effective wellbore radius, ft
S	skin factor, dimensionless
T	reservoir temperature, R
t	time, days
$\bar{t}_a$	normalized material balance pseudotime, days
T_a	new material balance pseudotime, days
t_{Dd}	dimensionless time based on drainage area and conventional pseudotime
V	total fluid volume, Mscf
z	real gas deviation factor, dimensionless
$\bar{z}$	real gas deviation factor at average reservoir pressure, dimensionless
z_i	real gas deviation factor at initial reservoir pressure, dimensionless

Greek letter variables

Φ	formation porosity, fraction
γ	Euler's constant=0.5772156649
γ_g	gas specific gravity
λ	Carter's drawdown parameter
μ	fluid viscosity, cp
μ_g	gas viscosity, cp
$\overline{\mu}_g$	gas viscosity at average reservoir pressure, cp
$\overline{\mu}_{gi}$	gas viscosity at initial reservoir pressure, cp
ρ	fluid density, lb/scf

Special subscript and operators

a	“adjusted” variable for gas well test analysis
D	dimensionless variable
M.P	matching point
p_{ss}	pseudosteady-state

analysis of boundary dominated gas reservoirs. Knowles (1996) presented a novel approach for estimating fluid properties during reservoir depletion. Knowles introduced a first-order polynomial function to model the non-linear viscosity-compressibility term ($\mu_{gi} c_{ti}/\mu_g c_t$) during boundary-dominated flow, which was valid for low pressure gas reservoirs. Ansah et al. (1996) expanded the works by Carter (1985) and Knowles (1996) with new functional models for analyzing production data from high pressure gas reservoirs.

Agarwal et al. (1999) analyzed the production data by using dual porosity type curve for oil and gas well with vertical fractures. Mattar and Anderson (2003) proposed a flowing material balance method based on modified version of Agarwal-Gardener rate/cumulative type curves. Mattar and Anderson (2005) presented a dynamic flowing material balance method to extend Mattar and McNeil (1998) technique for variable rate case. Their method required knowledge of pseudosteady state constant and need iterative scheme to compute gas-in-place. Mohammed and Enty (2013) presented a new flowing material balance equation, where they used a new time transform which they called “*rate normalized pseudo-cumulative*”. It is derived from pseudo-cumulative production, Gpn, rather than the actual cumulative production, Gp. They claimed that this new time function is superior to previously used time functions because it is independent of time step size. This method provided a direct approach to compute initial-gas-in-place when early pseudo-steady state (pss) line is observed..

The idea of pss line may be briefly explained here. For decline analysis, flow equation is developed for the pseudo-steady state flow regime (pss), where the flow/pressure behavior is influenced by the boundary effects, and the rate of pressure change is constant. The equation takes the form of a straight line on a Cartesian plot. However, the entire set of real data may not fall on a straight line. Thus detection of the straight line on the real data plot which is indicative of pss is an important task for the analysis. This straight line is termed as the pseudo-steady state line. The y-intercept is termed as the pseudo-steady state constant, bapss.

This paper focuses on the development and application of a solution for gas well performance through decline curve analysis.. This method does not require any extrapolation of the pss line or any iteration process. The equations are developed by coupling of normalized pseudopressure equation which is a function of cumulative production, and pseudosteady state flow equation. The flow rate is normalized by real gas pseudo-pressure drop, and the time is transformed into “*rate normalized pseudo-cumulative function*” from Mohammed and Enty.. The transformed data are then matched with Fetkovich composite type curve. This method leads to quicker estimation of original-gas-in-place (OGIP) and reservoir properties. The results obtained from proposed method are compatible with conventional pressure transient analysis.

2. Materials and methods

2.1. Theoretical method

2.1.1. Proposed method for gas DCA

Modern techniques of production datat analysis generally involve two main steps. First, the plotting function for y-axis is developed by