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A new approach for evaluating well deliverability in ultra-thick gas reservoirs

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ABSTRACT

Despite the recent activities in ultra-thick gas reservoirs worldwide, accurate evaluation of gas wells deliverability remains technically challenging. The success of such evaluation efforts relies heavily on proper consideration of the impact of ultra-thick pay zones. Deliverability equations and corresponding test methods are necessary to predict the deliverability of gas wells in ultra-thick gas reservoirs. In this paper, we develop a new model for calculating the pressure drop along the wellbore with varying mass flow rates from gas production profile testing. A new set of deliverability equations is proposed for gas wells in ultra-thick reservoirs. The new equations incorporate production testing data and are applicable to a wide reservoir pressure range. Correspondingly the deliverability test method for ultra-thick gas reservoirs was proposed. The integrated approach of utilizing deliverability equations and the proposed test method were validated against reservoir simulations that incorporate wellbore pressure drop. Good agreements between simulation and current analytical results were obtained for both low-pressure and high-pressure gas reservoirs. It is appropriate to apply the proposed deliverability equations and the corresponding test method to predict the deliverability of ultra-thick gas reservoirs. Further, validations using field data are in progress.

1. Introduction

In gas reservoirs with pay zone thickness greater than 50 m, such as South Pars/North Dome gas condensate field with reservoir thickness varied from 385 m for North Dome to 450 m for South Pars, Karachaganak gas condensate field with pay thickness of 1400+ m, and Puguang gas field with pay thickness of 400+ m, high gas flow rate and large pressure drop along the wellbore due to friction and gravity are often observed, whereas pressure drop within the formation is comparatively low. As a result, the slope in a binomial deliverability index plot ($(p_e{}^2 - p_{wf}{}^2)/q_{sc}$ or $(p_e - p_{wf})/q_{sc}$ versus q_{sc}) is very sensitive to flowing bottom hole pressure. For reservoir surveillance, pressure gauges placed in different locations have significant impact on deliverability analysis. In extreme cases, negative slope can occur, which makes accurate deliverability analysis very difficult for these ultra-thick gas reservoirs.

Vertical heterogeneity is commonly seen in ultra-thick gas reservoirs. Many researchers have studied the deliverability equation for ultra-thick multi-layered gas reservoirs since the 1960s. Tempelaar (1961) originally discussed the effect of oil production rate on the deliverability equation from a volumetric reservoir with multiple layers. Lefkovits et al. (1961) modified the Tempelaar-Lietz equations and investigated the pressure solution for commingled-layers system with the analytical method, assuming non-crossflow between layers. Fetkovich (1980) applied the approach developed by Lefkovits et al. (1961) for analyzing a layered reservoir, indicating that the reciprocal of decline-curve exponent increased to 0.2. To date, a number of ultra-thick gas reservoirs with high pressure and high sulfur content have been discovered. However, reservoir deliverability evaluations for these reservoirs remain rudimentary. Additionally, the impacts of wellbore pressure drop and flowing bottom hole pressure measurement on deliverability are not fully understood. Therefore, it is extremely important to develop a new approach to evaluate the deliverability for ultra-thick gas reservoirs, especially those of high pressure and temperature.

For evaluation of the deliverability in ultra-high pressure gas reservoir, Li et al. (2004) established deliverability equations using pseudo pressure and pressure square form, respectively. Furthermore, Li et al. (2009) defined a pseudo pressure calculation formula considering the stress sensitivity, which can be applied to the gas

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Nomenclature

q_{sc}	gas flow rate under standard condition, 10^4 m^3/day
q	total gas flow rate in the wellbore at each section of the reservoir, 10^4 m^3/day
Q	total gas flow rate in the wellbore at the top of the reservoir, 10^4 m^3/day
k	permeability, 10^{-3} μm^2
μ	gas viscosity, mPa s
μ_{ave}	average gas viscosity, mPa s
D	inner diameter of the tube, m
e	the absolute roughness of the tube inner surface, m
ψ	pseudo pressure, MPa/mPa s
β	velocity coefficient, m^{-1}
Z	gas deviation factor
T	reservoir temperature, K
h	thickness vector in the upward direction, m
H	effective thickness of gas layer, m
r_w	radius of the wellbore, m
r	random radius to the well axis, m
r_e	control radius of the gas well, m
S	skin factor, dimensionless
γ_g	relative density of gas, dimensionless
p_{pc}	pseudo critical pressure of gas mixtures, MPa
T_{pc}	pseudo critical temperature of gas mixtures, K
R	conventional gas constant, $R=0.008314$ MPa m^3/(kmol K)
a	unit transferring coefficient, dimensionless; in this work, $a=10^{-6}$, because the unit of pressure is transferred from Pa to MPa
$\overline{p}_R$	average reservoir pressure in the center of the reservoir, MPa
p_{wf}	flowing pressure in the wellbore in the center of the reservoir, MPa
$p_{wf,down}$	flowing pressure in the wellbore at the bottom of the reservoir, MPa
$p_{wf,up}$	flowing pressure in the wellbore at the top of the reservoir, MPa
$p_{e,down}$	reservoir pressure at the bottom of the reservoir, MPa
$p_{e,up}$	reservoir pressure at the top of the reservoir, MPa
C_0	static pressure gradient, MPa/m
$\rho_{e,ave}$	gas density under average static pressure, kg/m^3
ρ_{ave}	gas density under average flowing pressure, kg/m^3
ρ_{sc}	gas density under surface condition, kg/m^3
z	vector along the direction of upward well axis, m
v	gas velocity along the direction of upward well axis, m/s
π_D	perimeter of control volume, m
g	gravity acceleration, 9.81 m/s^2
θ	tube inclined angle, an angle between tube and horizontal direction, deg
α	well deviation angle, deg
p_i	pressure at the top of the ith section, MPa
$p_{ave,i}$	average pressure of the ith section, $p_{ave,i}=(p_{i-1}+p_i)/2$, MPa
$\rho_{ave,i}$	average gas density of the ith section, kg/m^3
$\mu_{ave,i}$	viscosity of the ith section under average pressure, mPa s
$R_{e,ave,i}$	Reynolds number of the ith section under average pressure, dimensionless
f	friction coefficient of gas flow, dimensionless
$f_{ave,i}$	friction coefficient of the ith section under average pressure, dimensionless
p_{ave}	average pressure of the total reservoir section, MPa
ρ_{ave}	average gas density of the total reservoir section, kg/m^3
μ_{ave}	average viscosity of the total reservoir section, Pa s
$R_{e,ave}$	average Reynolds number of the total reservoir section, dimensionless
f_{ave}	average friction coefficient of the total reservoir section, dimensionless
C	change rate of flow rate, (10^4 m^3/day)/m
C_1	gravity pressure gradient in the wellbore, MPa/m
C_2	friction pressure gradient in the wellbore, MPa/m
C_3	accelerated pressure drop in the wellbore, MPa
C_4	coefficient of pressure drop in the wellbore relating to square of gas flow rate, MPa/(10^4 m^3/day)^2
M	slope of the straight line in the plot of $((p_{wf,down}^2-p_{wf,up}^2)/q_{sc}^2)$ against $((p_{wf,down}+p_{wf,up})^2/q_{sc}^2)$, dimensionless
N	intercept of the straight line in the plot of $((p_{wf,down}^2-p_{wf,up}^2)/q_{sc}^2)$ against $((p_{wf,down}+p_{wf,up})^2/q_{sc}^2)$, MPa^2/($10^4$ m^3/day)^2

reservoir with higher pressure up to 25 MPa. However, ultra-thick gas reservoirs were not studied and the varying mass flow rate in the wellbore was ignored.

Recent investigations on pressure drop in vertical wellbore focus mainly on two-phase or multi-phase flows (Poettmann, 1951; Poettmann and Carpenter, 1952; Duns Jr. and Ros, 1963; Aziz et al., 1972; Beggs and Brill, 1973; Lawson and Brill, 1973; Mukherjee and Brill, 1985; Brill, 1987; Hasan and Kabir, 1988; Pucknell et al., 1993; Ansari et al., 1994; Salim and Stanislav, 1994; Al-Attar et al., 2011, 2012). By using these models, pressure distribution in the wellbore could be accurately predicted after the fluid flows into the wellbore, but the varying mass flow along the vertical wellbore was not considered in these models. Substantial amount of research (Dikken, 1990; Ihara et al., 1994; Novy, 1995; Ozkan et al., 1995; Zhou and Zhang, 1997; Liu et al., 2000; Zhang et al., 2002; Jansen, 2003; Hill and Zhu, 2008; Zhou and Guo, 2009; Akim and Jose, 2010; Lei et al., 2011) have been done on pressure drop calculation in horizontal wellbore and its effect on production. Most of them considered the varying mass flow in horizontal wellbore due to the continuous inflow along the long horizontal wellbore. However, very few works on developing a pressure drop model considering varying mass flows in long interval wellbore contacting with the ultra-thick reservoir have been found.

For measurement of the flowing bottom hole pressure, Yang et al. (2012) analyzed the abnormal characteristics of deliverability equation of the thick gas reservoir, and reported that the slope of deliverability index plot was sensitive to bottom hole pressure. The pressure gauges must be located in the reservoir section, which has larger contribution to gas production rather than the central region. The location of pressure gauges in ultra-thick reservoir is generally at the point with $0.5\Sigma Kh$. However, the varying mass flow rate was not considered in their study.

The pressure gauge is usually placed at a guessed depth within the interval, since it is very difficult to accurately pinpoint the central region of the reservoir in ultra-thick gas reservoirs before performing production profile testing. Hence, it is necessary to calibrate the data from pressure gauge for evaluating the deliverability of gas wells through pressure drop calculation. For gas reservoirs with layers less than 50 m, the model for pressure drop with constant mass flow rate