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A study of well test data interpretation model for water-bearing reservoirs with phase redistribution

Junxiang Zhang[1], Rui Deng[2], Haipeng Liang[2,*] and Jing Yang[2]

[1]Gas field Exploitation Department of PetroChina Changqing Oilfield Company, Xi'an, Shanxi, China
[2]School of Energy Resource, Chengdu University of Technology, Chengdu, Sichuan, China

*Corresponding author e-mail: 303453310@qq.com

Abstract. In China, plentiful marine reservoirs exist. Net pay thickness in individual gas reservoirs where partial penetration was performed can be hundreds of meters. Due to the influence of condensate water and formation, water phase separation phenomenon, where gas rose up and liquid moved down, and a morsel of water production emerged in some gas wells, which makes the build-up curves distorted and thus unable to be interpreted. On the basis of seepage theory and Laplace transformation, a seepage mathematical model and a well test interpretation model for gas wells with phase separation considered are developed to analyze the impact of such various elements as phase separation and partial penetration on the pressure and pressure derivative log-log plot. With practical data of well test in Xihu Sag, reliability analysis of the mathematical model mentioned above was demonstrated. Theoretical research results proposed in our study substantially improved the accuracy of well test interpretation for thick water-bearing gas reservoirs and laid a technical foundation of development of the similar oil & gas reservoirs.

1. Introduction

Such transient pressure tests as pressure buildup tests have been prevalently used as a reliable tool to estimate reservoir characteristics and other properties for years. Admittedly, pressure data acquired during the test are impacted by wellbore-related effects as well as reservoir properties. Phase redistribution is one of the wellbore effects, which exerts its main influence on wellbore storage. While wellbore storage is almost omnipresent, wellbore phase redistribution occurs in wells where two or more phases exist. It has been accepted that phase redistribution can cause anomalous pressure data in some oil and gas wells. A more sophisticated method is needed to avoid mistaking these effects as reservoir properties and achieve higher accuracy of well test interpretation for wells of this type.

As the gas reservoir exploitation are absorbing lasting attention in China, more and more importance is being attached to the research on production and exploitation of gas reservoirs while little has been made if any significant progress towards an agreeable investigation into multiphase flow in gas reservoirs. Hu Yong (2000) et al. have investigated the influence of multiphase flow of gas and water on the seepage in reservoirs. Li Xiaoping (2001) have addressed the methodology of research on productivity of reservoirs of gas-water multiphase. An analysis on steady and transient well test has been performed by Cheng Suimin *et al*. (2006). Li Chengyong et al. (2010) have addressed a mathematical model for low-permeability water-bearing gas reservoirs with the phase redistribution taken into account.

A considerable number of gas wells in Xihu Sag where an abundant resource of gas reservoirs with thick layers exist present distorted well test curves due to phase redistribution, which encumbers the interpretation of well test data and thus the exploitation of the gas field. With the discussion about the effects of phase redistribution on well test data and a validation based on factual data from Xihu Sag, a comprehensive investigation on the well test features of wells in Xihu Sag.

Fair[1] has presented a model for the transient pressure test data by considering phase redistribution as a parameters of wellbore storage. We have fused the model proposed by Fair with Duhamel's superposition principle.

2. The mathematical seepage model for water-bearing gas reservoirs

Fair et al. (1981) argued that the problem of phase redistribution was equivalent to the problem of variable bottom-hole storage. Therefore, it's a workable solution to revise the pressure data by superposition of pressure deviation function during phase redistribution. And the pressure deviation function for transient well test interpretation is given by

$$p_{\varphi D} = C_{\varphi D}(1 - e^{-t_D/\alpha_D}) \tag{1}$$

Where,

$$p_{\varphi D} = \frac{khp_{\varphi}}{1.842\times10^{-3}qB\mu}, \quad C_{\varphi D} = \frac{khC_{\varphi}}{1.842\times10^{-3}qB\mu}, \tag{2}$$

And

$$t_D = \frac{3.6kt}{\varphi\mu C_t r_w^2}, \quad \alpha_D = \frac{3.6k\alpha}{\varphi\mu C_t r_w^2} \tag{3}$$

Most of various theoretical researches referring to phase distribution are dependent on the exponential function proposed by Fair or the error function suggested by Hegeman since it has been proved that these formations are adequately consistent with laboratory data and factual data. Consequently, based on Fair Model and Hegeman Model the mathematical model in this paper for well test interpretation of wells with liquid loading is given by

$$\begin{cases} \dfrac{\partial^2 p_D}{\partial r_D^2} + \dfrac{1}{r_D}\dfrac{\partial p_D}{\partial r_D} = \dfrac{\partial p_D}{\partial t_D} \\ p_D(r_D,0) = 0 \\ p_{wD} = \left[p_D - S\left(\dfrac{\partial p_D}{\partial r_D}\right)\right]_{r_D=1} \\ C_D\left(\dfrac{dp_{wD}}{dt_D} - \dfrac{dp_{\varphi D}}{dt_D}\right) - \left[r_D \dfrac{\partial p_D}{\partial r_D}\right]_{r_D=1} = 1 \\ \lim\limits_{r_D-\infty}[p_D(r_D,t_D)] = 0 \end{cases} \tag{4}$$

Where,

$$p_{\varphi D} = C_{\varphi D}(1 - e^{-t_D/\alpha_D}) \qquad \textit{Fair Model} \tag{5}$$

And, if we let erf(x) is the error function

$$p_{\varphi D} = C_{\varphi D} erf(t_D/\alpha_D) \qquad \textit{Hegeman Model} \tag{6}$$

3. Analysis of the pressure behaviour

With Stehfest numerical inversion, the semi-analytical solution of the model can be obtained by solving simultaneously and thus analyses on effects of $C_{\varphi D}, \alpha_D$ the perforated thickness, the location of perforation *et al.* on the phase redistribution. Five flow periods, listed as following, can be clearly recognized on a pressure and pressure derivative log-log type plot (Fig.1).

1) I is named as well the storage period where the pressure curve and pressure derivative overlap each other and share a unit slope since it is influenced by the well storage effect.
2) II is the phase redistribution period where gas rose up and liquid moved down. The derivative curve meander as a hump appending to the unit slope of the previous period, which is a distinctive feature of phase distribution.
3) III is the local radical flow period. The curve presents a linear portion characteristic of a slope of negative one, which is the result of the radical flow through the perforation.
4) IV is the period of spherical flow where a linear segment with slope -1/2. This stage indicates layers, in addition to perforated layers, begin to give a considerable contribution to the overall flow, turning plane radical flow to spherical flow.
5) V is the pseudo-radial flow, distinguished by its horizontal linear portion with value 0.5, which is a remarkable sign that the whole system has obtained a state of equilibrium.

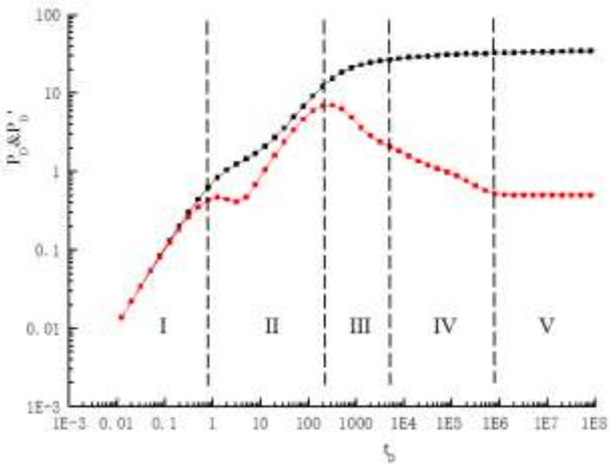

Fig. 1 A typical pressure and pressure derivative log-log plot of vertical wells with phase redistribution in thick water-bearing reservoirs.

4. Field Application in Xihu Sag

Production well HY1-1-3, spud-in on 6th Dec. 2013, was completed on 5th Nov. 2014 with 4468m total depth. Details of various parameters are listed as Table 1.

Table 1. Parameters of HY1-1-3 according to logging data interpretation

Parameters	Values	Parameters	Values
Apparent Net Pay Thickness(m)	69.1	Liquid Density(g/cm^3)	1.154
Perforation Thickness(m)	61.5	Mud Density(g/cm^3)	1.2
Porosity	7.1%	Mud Viscosity(S)	45
Water Saturation	54.9%	Formation Temperature(℃)	157
Permeability(mD)	0.38	Formation Pressure(MPa)	45.8
Concentration of Cl^-(mg/L)	38500	Formation Pressure Coefficient	1.15

The pressure and pressure derivative separated from each other at the early time, which conforms to the characteristic of phase redistribution in well bores (Fig2). According to this and the declination of the curve at the late stage, we, taking the geological settings of the reservoir into account, adopt the well test interpretation mathematical model for homogeneous gas reservoirs with closed outer boundary and phase redistribution considered to analyze the practical well test data, and the result was as the following Table 2.

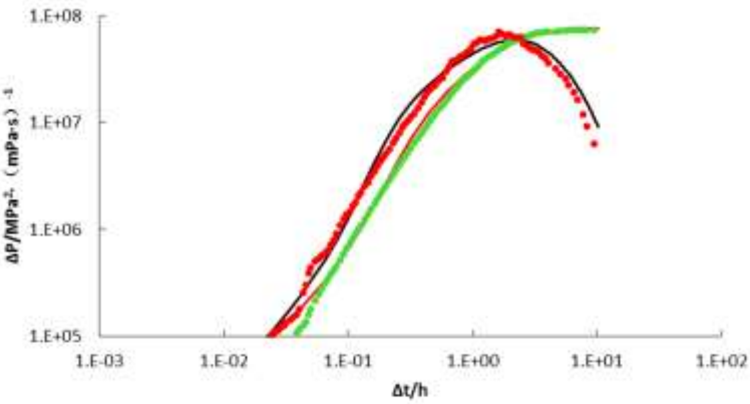

Fig. 2 Diagnostic log-log plot of HY1-1-3 well test data.

Table 2. Well test interpretation result of HY1-1-3

Parameters	Values
Extrapolated Formation Pressure (MPa)	52.9596
Formation Coefficient (mD•m)	2.56
Skin Coefficient	10.3
Well Storage Coefficient	0.0963
α_D	0.48

5. Conclusion

(1) An well test interpretation model for wells affected by phase redistribution was developed in this investigation, and the result shows that the hump and the negative pressure derivative on the log-log plot are the critical features to identify the occurrence of the phase redistribution.

(2) For thick water-bearing gas reservoirs, the phase redistribution is influenced, mainly, by $C_{\varphi D}$, α_D and the perforation thickness.

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