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Available online at www.sciencedirect.com
ScienceDirect
Natural Gas Industry B xx (2018) 1—10
www.elsevier.com/locate/ngib

Research Article

# An abnormality of productivity indicative curves of multi-layer gas wells: Reason analysis and correction method☆

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Received 17 January 2018; accepted 25 March 2018

## Abstract

An abnormality tends to occur in the productivity indicative curves in the process of productivity test interpretation of multi-layer gas wells, resulting in the failure of solutions to their productivity equations and absolute open flow rates. To figure out the reasons for such an abnormality, we established a full-hole calculation model considering the coupling of wellbore variable mass flows and reservoir seepages to calculate a gas production profile and wellbore pressure distribution of a multi-layer productive gas reservoir. Then, based on the analysis of the gas production profile and wellbore pressure distribution characteristics of gas wells at different gas production rates, the root cause for the abnormality in the productivity indicative curves of multi-layer gas wells was analyzed, and a corresponding correction method was proposed and validated based on some examples. And the following research results were obtained. First, there are two reasons for the abnormal productivity indicative curves of multi-layer gas wells. On the one hand, there is a variable mass pipe flow in the wellbore of multi-layer sections and a flowing pressure gradient decreases with the increase of well depth. And the flowing pressure in the middle of the reservoir which is converted based on the flowing pressure gradient above the pressure gauge is higher than the real value. On the other hand, the pressure in the multi-layer producing sections doesn't realize a balance after well shutdown for a short time, so the measured static pressure is greater than the one measured when the pressure of each layer gets balanced after well shutdown for a long time. Second, the flowing pressure obtained from the productivity test interpretation of multi-layer gas producer shall be converted based on the pressure measured by the pressure gauge within 200 m above the reservoir top and it is necessary to adopt the static pressure measured after the balance of wellbore pressure. Third, the reliability of the model, the rationality of the abnormality reason analysis and the validity of the correction method are verified based on calculation examples and cases. It is concluded that the research results provide a technical support for the productivity evaluation of multi-layer gas wells.


*Keywords:* Multi-layer gas reservoir; Commingling; Productivity test; Indicative curve; Variable mass flow; Abnormality correction; Flowing pressure; Static pressure

## 0. Introduction

Multi-layer gas reservoirs are characterized by multiple reservoir layers, large total thickness, large layer span, high formation pressure and high gas well production rate. In China, multi-layer gas reservoirs include the gas reservoirs of Changxing and Feixianguan Fms in Puguang Gas Field and Sebei Fm in Sebei Gas Field, and Dabei 1 gas reservoir, etc. An abnormality tends to occur in the productivity indicative

☆ This is the English version of the originally published article in Natural Gas Industry (in Chinese), which can be found at https://doi.org/10.3787/j.issn.1000-0976.2018.03.006.

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Peer review under responsibility of Sichuan Petroleum Administration.

https://doi.org/10.1016/j.ngib.2018.03.004

curves of multi-layer gas wells in the form of hump, concave, negative slope.

The abnormality may occur due to multiple reasons. First, since the pressure gauge is n't run to the middle of the producing pay, and the liquid accumulated at the bottom hole is drained out of the hole gradually with the increase of the test rate, the calculated pressure will be lower than the real value when the pressure in the middle of the producing pay during the low-production test is converted on the basis of the gas column pressure gradient. As a result, negative slope occurs in the productivity indicative curve. Second, when the back pressure of multi-layer gas wells is low, the low pressure layers begin to work, leading to concave abnormality in the productivity indicative curve. Third, as the test rate and the production pressure difference increase, the permeability near the wellbore is improved after the blockage is removed gradually. As a result, the concave abnormality occurs in the productivity indicative curve. These abnormalities bring difficulties to productivity evaluation. Therefore, many scholars have proposed correction methods [1−16], but few scholars have analyzed the correlation between the abnormalities in productivity indicative curves and the variable mass flow of the wellbore corresponding to the reservoir during the production, the non-uniformity of gas production profile, the nonlinear distribution of wellbore pressure and the wellbore pressure distribution during well shutdown based on the coupling between the reservoir seepage and the wellbore variable mass pipe flow.

If the producing pay is a single layer, the mass flow rate in the wellbore is constant. If there are multiple gas layers in a gas well, the gas mass flow rate is constant in the wellbore corresponding to the reservoir top to the wellhead, but changes gradually in the wellbore from the reservoir bottom to the top. The fluid in each section of the reservoir flows into the wellbore separately, and its flow rate is related to the bottom hole flowing pressure of each section. If it doesn't flow from the lower part to the higher part, the mass flow rate in the wellbore corresponding to each reservoir section increases gradually from the lower part to the higher part, so the wellbore flowing pressure drop model with the constant mass flow rate is not suitable for calculating the wellbore pressure drop of the multi-layer gas wells. There is variable mass flow in the wellbore and the gas production profile and the wellbore pressure distribution are affected mutually. Therefore, it is necessary to establish a calculation model with the coupling of reservoir seepage and wellbore pipe flow.

Many scholars have worked on the wellbore pressure drop calculation formulas considering variable mass flow [17−22]. Lei Dengsheng et al. [17], Zhou Shengtian and Zhang Qi [18], and Wang Lei and Zhang Shicheng [19] assumed that the flow rate from the reservoir to each section of a horizontal well was equal. Liu Xiangping et al. [20], Zhou Shengtian and Guo Xixiu [21], and Jiang Zhenqiang et al. [22] deemed that the flow rate from the reservoir to each section of a horizontal well was not equal, the flow rate in each section of the horizontal well was closely related to the flowing pressure in each section, and the accurate calculation method was to establish a coupling model to solve the flow rate from the reservoir to each section and the wellbore pressure distribution. Relevant studies show that coupling calculation shall also be conducted on the reservoir seepage and the wellbore pipe flow when the fluid production rate in each section and the wellbore pressure distribution during the production or the shutdown of commingled gas producing wells in multi-layer gas reservoirs are calculated. Therefore, it is in urgent need to establish a reservoir seepage-wellbore pipe flow coupling model for the commingled producing wells in multi-layer thick gas reservoirs to figure out the wellbore pressure distribution and the gas production profile considering the variable mass flow. After the root cause for the abnormality in the productivity indicative curves of multi-layer gas wells was analyzed, the correction methods were proposed. These study results provide a support for the productivity evaluation of multi-layer gas wells.

## 1. Abnormality in the productivity indicative curves of multi-layer gas wells

One actual multi-layer gas well is taken as an example. The cores taken from the reservoir where the well is located has the maximum porosity of 3.85%, minimum porosity of 0.52%, average porosity of 2.04%, maximum permeability of 10.00 mD, minimum permeability of 0.01 mD and average permeability of 0.20 mD. The total thickness of the reservoir is 71.60 m. The reservoir is of fractured-porous type with fractures and throats as the flowing pathways, and fractures are locally developed. The natural gas is mainly composed of $CH_4$ (96.15%), and its relative density is 0.5844.

When this well was tested after acidizing treatment, the pressure gauge could not be run to the middle of the reservoir to measure the bottom hole flowing pressure since there was a bayonet tube packer below the completion string. Therefore, the pressure gauge was run to 160 m above the reservoir top (VD 3350 m), i.e., 3190 m, and it was kept at this position during the well test. In order to avoid the effect of bottom hole plugging on productivity test due to the gradual discharge of residual acid when the test output in increasing, it was suggested to measure the production rate and the pressure in four operating systems in a production decline order. In order to improve the accuracy of test data in each operating system, it was proposed to run the pressure gauge in each system to measure the bottom hole flowing pressure and keep it for a long time to reach a stable state. The productivity test data are shown in Table 1. After data processing, the abnormality of negative slope is discovered in the productivity indicative curve. As a result, the productivity equation and the absolute open flow rate could not be solved. The cause for the abnormality is analyzed as follows. First, the test rate decreased gradually and no liquid was produced out of the gas well at a high production rate. It is indicated that the residual acid had been completely flown back before the test, so there is no effect of gradual drainage of residual acid on the blockage removal at the bottom hole. Second, no liquid was produced out of the gas well in any operating system, so the effect of