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Research article

Performance evaluation on water-producing gas wells based on gas & water relative permeability curves: A case study of tight sandstone gas reservoirs in the Sulige gas field, Ordos Basin☆

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Abstract

An outstanding issue in the oil and gas industry is how to evaluate quantitatively the influences of water production on production performance of gas wells. Based on gas–water flow theories, therefore, a new method was proposed in this paper to evaluate quantitatively the production performance of water-producing gas wells by using gas & water relative permeability curves after a comparative study was conducted thoroughly. In this way, quantitative evaluation was performed on production capacity, gas production, ultimate cumulative gas production and recovery factor of water-producing gas wells. Then, a case study was carried out of the tight sandstone gas reservoirs with strong heterogeneity in the Sulige gas field, Ordos Basin. This method was verified in terms of practicability and reliability through a large amount of calculation based on the actual production performance data of various gas wells with different volumes of water produced. Finally, empirical formula and charts were established for water-producing gas wells in this field to quantitatively evaluate their production capacity, gas production, ultimate cumulative gas production and recovery factor in the conditions of different water–gas ratios. These formula and charts provide technical support for the field application and dissemination of the method. Study results show that water production is serious in the west of this field with water–gas ratio varying in a large range. If the average water–gas ratio is 1.0 (or 2.0) $m^3/10^4$ m^3, production capacity, cumulative gas production and recovery factor of gas wells will be respectively 24.4% (or 40.2%), 24.4% (or 40.2%) and 17.4% (or 33.2%).

Keywords: Water saturation; Relative permeability; Water–gas ratio; Production capacity; Cumulative gas production; Recovery factor; Ordos Basin; Sulige gas field; Tight sandstone gas reservoir

In the Sulige gas field, Ordos Basin, more and more gas wells are now producing water, which is unfavorable for long-term stable production and gas recovery because daily gas output and cumulative production would definitely decline and the gas wells would also be killed to lose deliverability. But there are few proved techniques to evaluate the gas production of a water-producing gas well. As per literature [1–15], the productivity may be estimated by converting water production into gas production or changing the permeability around the wellbore or using the deliverability equation derived based on the principle of mass conservation. These methods have not been widely used in practice due to their inefficiencies or imperfection. In this paper, a new approach was proposed using gas–water relative permeability curves to assess the deliverability of a water-producing gas well.

1. Gas & water relative permeability curves

Gas & water relative permeability curves are the theoretical basis to describe gas–water flow. The symbols employed here

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are cited from SY/T5345-2007 Test Method for Two-Phase Relative Permeability in Rock, which details the specifications of relative permeability measurement for a two-phase fluid.

Gas & water relative permeability is respectively defined as follows.

$$K_{rg} = \frac{K_{ge}}{K_g(S_{ws})} \tag{1}$$

$$K_{rw} = \frac{K_{we}}{K_g(S_{ws})} \tag{2}$$

As per the definition, gas relative permeability ranges between 0 and 1. In a state of saturation with irreducible water, only one-phase fluid flow of gas exists in the rock, when gas relative permeability is equal to 1 and there is no water production in the gas well. Gas relative permeability decreases with water saturation and finally approaches zero, when water relative permeability reaches a peak. Standard variations of gas & water relative permeability with water saturation are shown in Fig. 1; however, the actual variations are presented as demonstrated in Fig. 2. These trends are not in agreement with the industry standard and should not be used anymore.

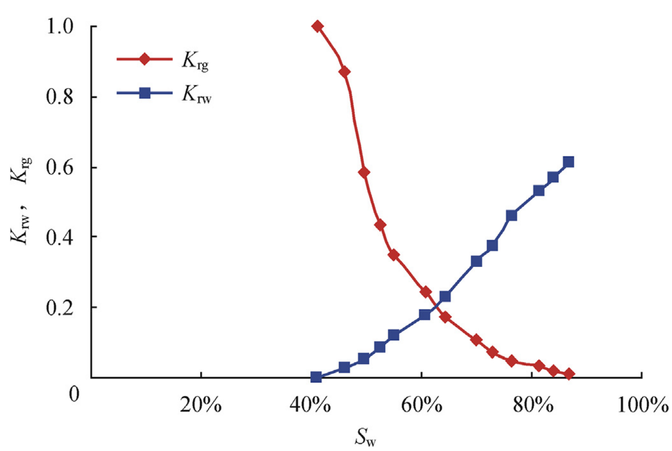

Fig. 1. Standard gas & water relative permeability vs. water saturation.

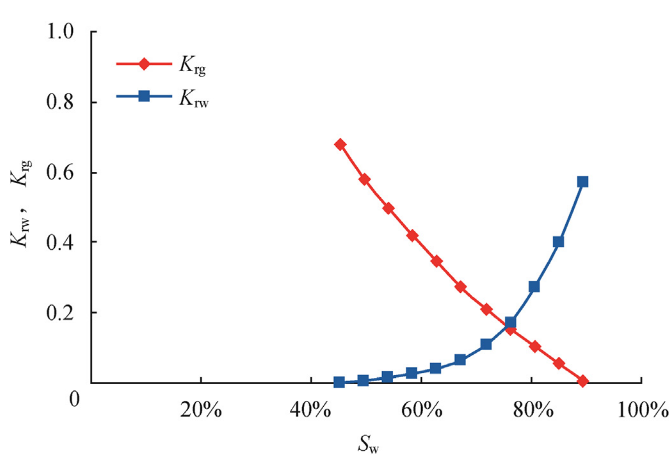

Fig. 2. Actual gas & water relative permeability vs. water saturation.

2. Gas recovery evaluation

Gas recovery evaluation for a water-producing gas well involves the impacts of water production on gas productivity (which has been discussed in many published papers) and ultimate cumulative gas production, i.e. expected ultimate recovery (which has not been published yet). This paper and reference [16] quantitatively discuss what and how the gas recovery could be evaluated for tight sandstone gas reservoirs with strong heterogeneity. The objective is to formulate a portfolio of techniques for enhanced gas recovery.

2.1. Deliverability evaluation

What should be noted is that the deliverability, i.e. productivity or absolute open flow capacity, refers to gas yield at the maximum draw down pressure, while the production refers to gas yield at a given draw down pressure.

The deliverability and production are formulated using the following binomial equation [17—19].

$$p_R^2 - p_{wf}^2 = Aq_g + Bq_g^2 \tag{3}$$

The deliverability of a gas well is

$$q_{AOF} = \frac{-A + \sqrt{A^2 + 4Bp_R^2}}{2B} \tag{4}$$

The gas yield at a draw down pressure is

$$q_g = \frac{-A + \sqrt{A^2 + 4B\left(p_R^2 - p_{wf}^2\right)}}{2B} \tag{5}$$

The deliverability and gas yield could be estimated if A and B are known.

As per the literature, the coefficients of the binomial equation could be expressed as

$$A = \frac{84.84\mu ZTp_{sc}}{KhT_{sc}}\left[\lg\left(\frac{0.472r_e}{r_w}\right) + 0.434S\right] \tag{6}$$

$$B = \frac{36.9\mu ZTp_{sc}D}{KhT_{sc}} \tag{7}$$

Define

$$C_1 = \frac{84.84\mu ZTp_{sc}}{hT_{sc}}\left[\lg\left(\frac{0.472r_e}{r_w}\right) + 0.434S\right] \tag{8}$$

$$C_2 = \frac{36.9\mu ZTp_{sc}D}{hT_{sc}} \tag{9}$$

For a gas well without water production, i.e. water saturation equal to irreducible water saturation, effective permeability K in Eqs. (6) and (7) is equal to K_g (S_{ws}), then A and B could be estimated by

$$A = C_1/\left[K_g(S_{ws})\right] \tag{10}$$

$$B = C_2/\left[K_g(S_{ws})\right] \tag{11}$$