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Research article

Design philosophy and practice of asymmetrical 3D fracturing and random fracturing: A case study of tight sand gas reservoirs in western Sichuan Basin

Guo Jianchun, Gou Bo*

State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China

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Abstract

At present two technical models are commonly taken in tight gas reservoir stimulation: conventional massive fracturing and SRV fracturing, but how to select a suitable fracturing model suitable for reservoir characteristics is still a question waiting to be answered. In this paper, based on the analysis of geological characteristics and seepage mechanism of tight gas and shale gas reservoirs, the differences between stimulation philosophy of tight gas reservoirs and shale reservoirs are elucidated, and the concept that a suitable stimulation model should be selected based on reservoir geological characteristics and seepage mechanism aiming at maximally improving the seepage capability of a reservoir. Based on this concept, two fracturing design methods were proposed for two tight gas reservoirs in western Sichuan Basin: asymmetrical 3D fracturing design (A3DF) for the middle-shallow Upper Jurassic Penglaizhen Fm stacked reservoirs in which the hydraulic fractures can well match the sand spatial distribution and seepage capability of the reservoirs; SRV fracturing design which can increase fracture randomness in the sandstone and shale laminated reservoirs for the 5th Member of middle-deep Upper Triassic Xujiahe Fm. Compared with that by conventional fracturing, the average production of horizontal wells fractured by A3DF increased by 41%, indicating that A3DF is appropriate for gas reservoir development in the Penglaizhen Fm; meanwhile, the average production per well of the 5th Member of the Xujiahe Fm was 2.25×10^4 m^3/d after SRV fracturing, showing that the SRV fracturing is a robust technical means for the development of this reservoir.

Keywords: Tight gas; Shale gas; Fracturing (rock); Asymmetrical 3D fracturing; Seepage element; Fracture randomness; SRV fracturing; Western Sichuan Basin

Tight gas reservoirs refer to the gas reservoirs with matrix permeability of less than or equal to 0.1 mD, which have no natural deliverability, or can not reach industrial flow rate unless reservoir stimulation techniques are utilized [1]. The geological characteristics of this kind of reservoir make hydraulic fracturing or acidizing necessary to improve the seepage conditions, and ultimately to achieve high-efficient development of this kind of gas reservoir. In China, hydraulic fracturing of tight gas reservoirs has gone through three phases: separate-layer fracturing for vertical wells, massive hydraulic fracturing, and multi-staged fracturing for horizontal wells. The main purpose of these techniques is to create long double-wing hydraulic fractures, connect reservoirs far from wellbores, increase seepage area and accordingly improve productivity [2]. Recently, the successful application of stimulated reservoir volume (SRV) combined with horizontal well completion in shale gas development triggers a new revolution in hydraulic fracturing [3,4]. Engineers in China have attempted to apply shale gas development modes in tight gas reservoir development, but achieved quite different responses [5]. Currently, the concepts of SRV and classical massive hydraulic fracturing aiming at creating long fractures exist side by side, making it a puzzle question what fracturing model should be taken to make full use of the reserves in reservoirs with complex characteristics. In this paper, we

* Corresponding author.
E-mail address: gouboyouxiang@163.com (Gou B.).
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analyzed the stimulation concept differences between tight gas reservoirs and shale gas reservoirs based on their geological and seepage characteristics, and proposed different fracturing design concepts for different types of tight sandstone reservoirs in western Sichuan. According to field application experiences, tight gas reservoir fracturing treatment concepts were summarized in this paper.

1. Hydraulic fracturing concept for tight gas reservoirs

1.1. Differences between tight gas reservoirs and shale gas reservoirs

Tight gas and shale gas are currently two kinds of unconventional resources in hot exploration and exploitation in China. Tight gas reservoirs include tight carbonate reservoirs, tight sand reservoirs, and tight volcanic reservoirs, among which, tight sand reservoirs are the focus of the present fracturing (also the reservoirs discussed in this paper). There are significant differences in geological characteristics, seepage mechanism, and reservoir properties between shale gas and tight sand gas reservoirs (Table 1) [6−8], which directly influences fracturing concepts for them.

1.2. Fracturing concept for tight gas reservoirs

1.2.1. Fracturing concept differences between tight gas and shale gas reservoirs

1.2.1.1. Differences in reservoir properties and seepage characteristics. Compared with conventional sand gas reservoirs, tight sand reservoirs are lower in porosity, permeability, and their percolation is strongly influenced by threshold pressure gradient, stress sensitivity, and slippage effect [9,10], however, the seepage mechanism is still classical flow of free gas from pores to artificial fractures (hydraulic fractures) of "long seepage distance". Therefore, the main purpose of tight gas reservoir fracturing is still to create long double-wing fractures with certain conductivity, and thus to increase seepage area (Fig. 1a).

Shale gas reservoirs have pore throat diameter much smaller than tight gas reservoirs (Table 1), and nano-Darcy permeability, so shale gas flows a very short distance in the whole production cycle. Considerable driving force is needed if shale gas is to flow such a long distance as in tight gas reservoirs. Therefore, for shale gas reservoirs, hydraulic fracturing is required to "smash" the permeable formation, generate complex fracture networks and hence, increase the overall permeability of shale formation, so the fluid in the reservoir can flow from matrix to fractures. This is the concept of SRV [4,11]. The essence of SRV is to smash the reservoir, form more random fractures and generate a new "artificial gas reservoir". The more smashed the reservoir, the more random the fracture network, the shorter the gas flow distance, the more easily free gas and adsorbed gas will be released from reservoir matrix. The characteristics and seepage features of shale gas reservoirs indicate that increasing the randomness of fractures is the optimal choice for their effective development (Fig. 1b).

1.2.1.2. Differences in geological features. Although tight gas reservoirs and shale reservoirs are both continuous accumulation, the former is commonly found in lenticular, multilayered and block-shaped channel sand bodies [6]. Due to the strong heterogeneity of channel sand bodies, hydraulic fractures have to be controlled within the sand body to make full use of the reserves. Therefore, the key in tight gas reservoir fracturing design is how to deploy hydraulic fractures to fully stimulate the reservoir in three dimensions (Fig. 2a).

Shale reservoirs are typically "continuous" ones, featuring in-situ generation and storage. The objective of shale reservoir fracturing is to select layers with high gas saturation, high

Table 1
Comparison of tight sand reservoirs and shale gas reservoirs.

Items	Tight sand gas	Shale gas
Distribution features	In the center of a basin or slope	Close to the basin subsidence -deposition center
Burial depth	1500−4500 m	200−3500 m
Aggregation effect	High production in dissolution and fractured part of the reservoir	Disperse in shale, enriched in fractured part of the reservoir
Relationship between source rock and reservoir rock	Direct contact or adjacent to each other	Source-reservoir-caprock in one
Accumulation mode	Superposed lens, multilayered sand mass and block sand mass	"Continuity" gas reservoir
Gas occurrence	Partially controlled or not controlled by buoyancy, exist in pores in a free state	Mainly in an absorbed or a free state, only a little dissolved gas
Porosity	$<10\%$	$<6\%$
Pore throat diameter	25−900 nm	5−200 nm
Permeability	<0.1 mD	1×10^{-6} mD
Seepage mechanism	Flow in porous media under pressure difference	Desorption and diffusion occurs in Nanoscale fractures and micro-fractures under pressure difference
Well type	Vertical, horizontal, slant, and S-shaped wells	Horizontal wells
Recoverable reserves in China	$(15-20) \times 10^{12}$ m^3	$(15-20) \times 10^{12}$ m^3