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RESEARCH PAPER

Progress in key technologies for evaluating marine shale gas development in China

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Abstract: The Lower Paleozoic Longmaxi and Qiongzhusi Formatiion shale plays were taken as research objects to summarize the geologic and reservoir characteristics of marine shale gas in China. Based on the theory and technology achievements made during the twelfth five-year plan, a key index system was established to evaluate shale gas well production effect in China, and a comprehensive classification was consequently presented by integrating geological statistical indexes and economic evaluation indexes; to characterize the complex fracture network formed by fracturing, a generalized analytical model was established by incorporating fractal and continuum geometry theory to capture the transient behavior of such fractured horizontal well throughout production life. An associated probabilistic analysis, based on the Monte Carlo simulation was presented by linking a probabilistic worksheet with the analytical model, and then used to determine a range of possible outcomes (i.e., EUR, decline rate and production time). Meanwhile, an optimization approach for development parameters, including fractured horizontal segment, fracture geometry (i.e., fracture length, conductivity, number), well spacing and drawdown management was advanced. There are still many unresolved problems on geologic theory, flow mechanism and productivity evaluation method, development technical policy and economic benefits, which limit large-scale and high-efficiency exploitation of shale gas resource in China.

Key words: shale gas; reservoir characteristics; productivity evaluation; horizontal section length; fracture parameter; development well spacing; production system

Introduction

Shale gas, which is a new kind of energy resource, mainly exists in fine-grained mudstone or shale in absorbed and free states. Benefiting from the favorable policy environment and continuous technological breakthroughs since the 1990s, American shale gas industry has made great progresses; shale gas in multiple sets of commercialized development in marine shale formations from Paleozoic to Cenozoic has been achieved developed commercially. According to a the latest statistics from Energy Information Administration (EIA)[1], shale gas production of United States (US) increased amounted to 429.4 billion cubic metres meters in 2015, which occupies 46.1% of America's total gas output. Shale gas in China has a wide distribution, numerous favorable strata, and recoverable available resources of 12.85 trillion cubic meters, ranking among the top in the world[2], in which. Those strata mainly are marine shale. At present, great advancement has been achieved in the lower Paleozoic Longmaxi and Qiongzhusi shale formations in Sichuan Basin and its peripheral regions. A series of productivity constructions in Fuling, Changning-Weiyuan, Fushun-Yongchuan and Zhaotong have been initiated, marking the preliminary stage of large scale development of shale gas. This paper compares the shale gas developing conditions between China and United States, reviews the developing practice and technological innovations and gives a summary of progress in key technologies of evaluating shale gas development in the past few years, in the hope of providing instructive references for the development of China's shale gas industry.

1. Geologic and reservoir characteristics of marine shale gas in China

1.1. Geologic characteristics of marine shale gas in China

Compared with Barnett, Marcellus, Haynesville and Eagle Ford shale gas fields in the United States, China's shale gas plays have the typical geologic characteristics below.

(1) Deep burial depth of China's marine shale. The Lower Cambrian Qiongzhusi Formation and Upper Ordovician Wufeng Formation-Lower Silurian Longmaxi Formation are older than most shale formations in Northern America, so they

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have larger burial depth in general except for local uplifts in the Sichuan Basin and its edge. For example, Qiongzhusi Formation is about 2 000 m deep at the basin edge, but over 8 000 m deep inside the basin. Large burial depth on one hand adds difficulty and risk to shale gas development, and set higher requirements on development processes, on the other hand, with the increase of depth, formation pressure increases, and abundance of shale gas increases significantly too.

(2) Complex geologic structure and abundant faults of marine shale formations in China. After deposition, the two shale formations of Paleozoic have undergone a series of tectonic evolution from Mesozoic to Cenozoic which had important effect on shale gas preservation. While changing the geometry of the basin, tectonic movements can cause the formation of natural fracture system. Natural fracture can improve permeability of organic-rich shale, and is one kind of pathways for shale gas to move from matrix pores to well, and is the necessary condition for forming complex fractured systems by artificial fracturing.

(3) At present, the developed marine shale gas fields with shallow burial depth in China are located in the low mountains and hills around the verge of Sichuan Basin, where the ground surface is rugged. Rugged landscape and vulnerable ecological environment cause difficulties in constructing drilling sites and gas pipelines, adding difficulties to the overall shale gas development.

1.2. Reservoirs of marine shale gas in China

Compared with conventional oil and gas reservoirs, marine shale gas formations have distinct differences in “sweet spot” scale, gas occurrence state, types of reservoir space and evaluation parameters.

The high quality marine shale reservoirs in southern China mainly deposited in deep shelf environment, where the terrain was gentle and broad, and the paleoclimate, paleoenvironment and paleogeography were consistent in a large scope, so the thickness of reservoir is stable on the plane. Different from the lenticular scattered distribution of tight gas effective reservoir sand bodies, the scale of “sweet spots” of high quality shale ranges from dozens to hundreds of square kilometers[3].

Part of the shale gas accumulates in the pore space in free state and the other part is absorbed on the surface of organic matter and clay minerals. The free gas content per unit volume is controlled by porosity and gas saturation, while the absorbed gas content depends on the absorbability of shale, which is affected mainly by organic content, temperature and pressure. Langmuir isotherm model is commonly used to calculate the absorbed gas content currently.

Shale reservoir space is classified into two types, matrix pore and fracture. Matrix pores include clay or brittle mineral inter-crystalline pores, secondary dissolution pores and organic matter pores, and are mostly nano-scale with sizes of 2-200 nm. Fractures can be divided into macro and micro fractures according to their size. Researches have shown that matrix porosity is related to its total organic carbon (TOC) content and maturity. The matrix porosity increases with the rise of TOC[4], this trend, however, slows down or even reverse when TOC content is over 5%, this is because the organic-rich shale is low in pressure resistance, therefore, the organic matter pores are difficult to preserve. The relationship between maturity and micro-pore structure of shale has been proved complex, with the rise of maturity, micro-pores formed by hydrocarbon generation of organic matter increase gradually, but in this process, montmorillonite with large specific surface area, changes into illite-montmorillonite mixed-layer and finally illite and chlorite, making specific surface area and porosity of micro-pores between mineral grains decrease remarkably. Macro-fractures are more developed in regions with complicated geological structure (for example, orogenic belt at basin edge), while micro-fractures are more easily to form in formations with high content of brittle minerals.

Horizontal well drilling and artificial fracturing are the main technologies used for shale gas development due to the properties of shale gas reservoirs. Besides gas content, pressure coefficient, thickness of high quality shale and other traditional evaluation parameters, some engineering geological conditions should be taken into consideration in shale reservoir evaluation. Such engineering geological conditions include rock elastic modulus, poisson's ratio, difference of horizontal stresses and development of fractures, which determine the reservoir fracability and fracturing effect.

2. Development status of China’s marine shale gas

Shale gas exploration and development in China have made great breakthrough during the twelfth five-year plan period. A series of major theories, systematic innovations and technology progresses fueled commercial development of China's shale gas from 2014 to 2015. By the end of 2015, 198 evaluation wells, 393 horizontal wells of marine shale gas had been finished, 267 wells had been fractured and put into production, with the productivity of 77×10^8 m^3, and three marine shale gas demonstration areas, Fuling, Changning-Weiyuan and Zhaotong had been built.

The selection of “sweet spot”, optimized and accelerated drilling and volume artificial fracturing technologies have made major progress through research and test during the twelfth five-year plan, which has supported the transition of invalid resource to effective production, lowered the total investment of single well from 100 million Yuan in the early days to 7 0 million Yuan now, and brought about the rapid increase of shale gas production from 12.8×10^8 m^3 in 2014 to 44.6×10^8 m^3 in 2015. How to translate effectively production into scale production is the most important research direction in the thirteenth five year plan period.

According to the characteristics of marine shale gas in southern China, CNPC and SINOPEC have come up with the four modes of efficient exploration and development, “well