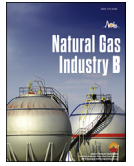




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Research Article

Prospect of shale gas recovery enhancement by oxidation-induced rock burst

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Abstract

By horizontal well multi-staged fracturing technology, shale rocks can be broken to form fracture networks via hydraulic force and increase the production rate of shale gas wells. Nonetheless, the fracturing stimulation effect may be offset by the water phase trapping damage caused by water retention. In this paper, a technique in transferring the negative factor of fracturing fluid retention into a positive factor of changing the gas existence state and facilitating shale cracking was discussed using the easy oxidation characteristics of organic matter, pyrite and other minerals in shale rocks. Furthermore, the prospect of this technique in tackling the challenges of large retention volume of hydraulic fracturing fluid in shale gas reservoirs, high reservoir damage risks, sharp production decline rate of gas wells and low gas recovery, was analyzed. The organic matter and pyrite in shale rocks can produce a large number of dissolved pores and seams to improve the gas deliverability of the matrix pore throats to the fracture systems. Meanwhile, in the oxidation process, released heat and increased pore pressure will make shale rock burst, inducing expansion and extension of shale micro-fractures, increasing the drainage area and shortening the gas flowing path in matrix, and ultimately, removing reservoir damage and improving gas recovery. To sum up, the technique discussed in the paper can be used to “break” shale rocks via hydraulic force and to “burst” shale rocks via chemical oxidation by adding oxidizing fluid to the hydraulic fracturing fluid. It can thus be concluded that this method can be a favorable supplementation for the conventional hydraulic fracturing of shale gas reservoirs. It has a broad application future in terms of reducing costs and increasing profits, maintaining plateau shale gas production and improving shale gas recovery. © 2017 Sichuan Petroleum Administration. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Keywords: Shale gas; Oxidization; Gas recovery; Rock burst; Organic matter; Pyrite; Conductivity

1. Introduction

The key of shale gas recovery enhancement is to improve the methane gas desorption and diffusion capacity. Hydraulic fracturing is conducive to improving the seepage capacity of shale gas reservoirs, but it still cannot solve the problem of low desorption, diffusion and transmission capacity of methane gas in nanopores. As a result, the gas deliverability of shale matrix is much lower than the gas transmission capacity in the fractures. Thus, the production rate of gas wells in the initial period of exploitation is exponentially decreasing [1–3]. As the pore size decreases, the methane desorption, diffusion and

transmission resistance increases and gas reservoir recovery decreases. For example, the recovery in shale gas reservoirs in the United States mostly ranges between 5% and 20%, but the recovery in Barnett shale gas reservoir is only 10%.

A large number of nano-scale pores are produced in organic matters. The spatial distribution of pyrite is closely related to organic matters. Organic matters and pyrite are closely related to the methane gas transmission path. They belong to the deposits under reductive environment [4], prone to oxidative dissolution. Therefore, due to the characteristics of fracturing fluid easy retention and difficult backflow, oxidizing fluid can be added into hydraulic fracturing fluid [5–12] to oxidize and dissolve the organic matter and pyrite, thus to produce a large number of dissolved pores and seams, and ultimately enhancing the conductivity of shale pores and seams.

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In this paper, based on the analysis of the influence of engineering geological characteristics of shale gas reservoirs on the gas transmission capacity, the feasibility of the technique of oxidation-induced shale rock burst is demonstrated and the application prospect of oxidation in the fracturing stimulation of shale gas wells and gas recovery enhancement is discussed.

2. Engineering geological characteristics and gas transmission capacity of shale gas reservoirs

2.1. Multi-scale space of pores and seams determines shale gas transmission capacity

Shale gas mainly occurs in the pores of organic matters and the intergranular pores of clay minerals, which are mainly nano-scale [13,14]. According to their sizes, pores are divided into micropores ($d < 2$ nm), mesopores ($2 \text{ nm} < d < 50$ nm) and macropores ($d > 50$ nm) [15–17]. The average diameter of shale pores is less than 100 nm and they are mainly mesopores and macropores [16–18]. Fractures are one of the controlling factors for shale gas transmission capacity [19–22], while shale fractures are mainly at the scale of macropores [19]. The methane gas in shale micropores and mesopores is dominated by desorption–Knudsen diffusion and slip flows, while the methane gas in shale macropores is dominated by viscous flow and Knudsen diffusion/slip [19,23]. According to the characteristics of multi-scale pores and seams of shale rocks, Alharthy et al. [19] proposed a “triple” pore network model of shale gas transmission and “serial” and “parallel” transmission mechanisms. In the “serial” transmission, shale gas transmits towards the micropores, mesopores and macropores in sequence; in the “parallel” transmission, gas in the micropores and mesopores transmits towards the macropores simultaneously.

2.2. Methane occurrence state affects shale gas transmission capacity

Natural gas in shale gas reservoirs consists of three parts: free gas in fractures, free gas and adsorbed gas in matrix pores such as organic pores and clay mineral intergranular pores. The proportion of adsorbed gas in the North American shale ranges from 20% to 85%. Adsorbed methane mainly occurs in micropores and mesopores. At this scale, the methane gas transmission mechanism is desorption–diffusion and slip flows, and the production rate and yield of adsorbed methane are lower than that of free methane in a larger–scale space [24–27]. In addition, the permeability of methane gas is significantly smaller than that of nitrogen and helium, since the adsorption of methane on the pore wall makes the effective transmission path smaller and increases the methane transmission resistance [28]. Methane adsorption affects the effective aperture of shale [29], which reduces the apparent permeability of shale nanopores [30,31].

2.3. Rich organic matter and pyrite is the prerequisite to enhancing shale gas transmission capacity via oxidation-induced rock burst

Organic matter is an important part of high-quality shale. Shale organic pores develop in organic matters, and organic pores are well developed and have a good connectivity in the high-over mature organic matters [32–35]. The organic carbon content of shale in the Lower Cambrian Niutitang Fm in the SE Chongqing region ranges from 2% to 10%, with an average of 7.0% [36]. The organic carbon content of the Chang7¹ Member of the Upper Triassic Yanchang Fm in the continental shale of the Ordos Basin is generally 4–12% [37]. The content of organic matter in the “sweet spots” of the Upper Ordovician Wufeng–Lower Silurian Longmaxi Fms in the Sichuan Basin is greater than 3.0%. Assuming that the density of organic matter is 1.2 g/cm³, the volume proportion of shale organic matter is 4–25%. The organic carbon content of shale in the Junggar Basin is up to 79.44% [38]. The occurrence state of shale organic matter is diverse [39–41]. According to the contact relation between organic matters and minerals, the occurrence state of organic matter is divided into four types [42]: striped, interstitial, film-like, and fragmental. Loucks et al. [43] classified shale organic matters into dense continuous, sparse continuous and disperse organic matters. Nie et al. [44] argued that shale organic matters were mainly distributed along micro-bedding surfaces or sedimentary discontinuity surfaces. This mode of organic matter occurrence was prone to produce interconnected organic pore networks with generally good permeability. Kuila et al. [45] argued that shale organic matters existed in the form of dispersed particles and continuous layers, and that the intergranular pore connectivity between granular organic matters and clay minerals was good.

As the most important sulfide mineral of black shale, pyrite (FeS₂) is a kind of diagnostic mineral rich in organic deposits [46–50]. Pyrite is common in shale gas reservoirs, with a content of 1–5%, and it is mainly in the shape of a strawberry or a mold ball and local enrichment blocks. The pyrite of idiomorphic crystal is few and the particle size ranges from several micrometers to tens of microns.

Organic matter and pyrite, both with active chemical properties, are probable to generate dissolved nano-scale pores and seams via oxidation. Anderson et al. [51] found that sodium hypochlorite solution and bromine water could efficiently remove organic matters in clay rocks. Under the oxidation of potassium permanganate (KMnO₄) solution, organic matters in soil are easily oxidized and decomposed [52]. For example, when the concentration of KMnO₄ solution is 0.3 mol/L, the oxidative decomposition rate of organic matter is between 60% and 98% [53]. Zhang Mengyan et al. [54] pointed out that when the organic matter in soil contacts with the oxidizing solution, the carbonyl could be oxidized to form carboxylic acid, and the aromatic carbon might open ring to form saturated aliphatic carbon and water molecule organic acid. Kuila et al. [45] studied the removal efficiency of shale organic matter using NaOCl solution. It was found that

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