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Research article

Theory and technique of permeability enhancement and coal mine gas extraction by fracture network stimulation of surrounding beds and coal beds

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Abstract

The existing reservoir stimulating technologies are only applicable to hard coal but helpless for soft coal, which is one of the main factors hindering the CBM industrialization in China. Therefore, it is urgent to develop a universal stimulating technology which can increase the permeability in various coal reservoirs. Theoretical analysis and field tests were used to systematically analyze the mechanical mechanisms causing the formation of various levels and types of fractures, such as radial tensile fractures, peripheral tensile fractures, and shear fractures in hydraulic fracturing, and reveal the mechanism of permeability enhancement by fracture network stimulating in surrounding beds and coal reservoirs. The results show that multi-staged perforation fracturing of horizontal wells, hydraulic-jet staged fracturing, four-variation hydraulic fracturing and some auxiliary measures are effective technical approaches to fracture network stimulation, especially the four-variation hydraulic fracturing can stimulate the fracture network in vertical and cluster wells. It is concluded that the fracture network stimulating technology for surrounding beds has significant advantages, such as safe drilling operation, strong stimulation effect, strong adaptability to stress-sensitive and velocity-sensitive beds, and is suitable for coal reservoirs of any structure. Except for the limitation in extremely water-sensitive and high water-yield surrounding beds, the technology can be universally used in all other beds. The successful industrial tests in surface coal bed methane and underground coal mines gas extraction prove that the theory and technical system of fracture network stimulating in surrounding beds and coal reservoirs, as a universally applicable measure, will play a role in the CBM development in China.

Keywords: CBM; Roof and floor; Surrounding bed mining layer; Fracture network stimulation; Permeability enhancement mechanism; Four-variation hydraulic fracturing; Technology

1. Introduction

Ground CBM development is greatly highlighted due to its three-fold significance in CBM resources exploitation, disaster and emission reduction. Eleven out of 13 coal basins in the US have realized CBM commercial development [1]; CBM production in Alberta, Canada, has soared rapidly in recent period [2]; and efficient CBM development has been achieved through multi-lateral horizontal wells in the Surat Basin, Australia [3,4]. In contrast, after arduous exploration for more than 30 years, CBM commercial development in China has been realized only in local regions.

It is well known that hydraulic fracturing is the key technology in CBM development. While it is applicable to elastic media in which propped-fractures can be created to increase conductivity and production, it can't do any good to soft coal, a kind of plastic media, which has been proved by a lot of practices and research [5]. Therefore, soft coal has become a problem in CBM development. Unluckily, more than half of

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the CBM resources is in the reservoirs with well-developed soft coal. It is difficult for the current active water & quartz sand fracturing technology to create long and wide propped-fractures in deep coal reservoirs with high geostress, where the gradually increasing stress-sensitive effect would result in serious proppant crushing, embedment and fracture closure, so the wells will become dead after a short period of gas production [6], which is the second problem in CBM development. It is difficult to make breakthroughs in large-scale commercial development of CBM due to the very two problems.

Underground coal mine gas extraction can be categorized into that without pressure relief and that with pressure relief [7]. The effect of the former completely depends on the original permeability of coal reservoirs, and is usually compensated through the increase of drilling quantities; in contrast, coal reservoir permeability can be increased more than a thousand times in the latter extraction mode. Protective layer mining is the most effective means to increase permeability and has been successfully applied in a number of wells with multiple coal layers [8,9]. With protective layer production, coal reservoir permeability can be greatly increased, a large amount of gas can also be extracted from adjacent surrounding bed fracture zones. Large-scale rapid gas extraction can be achieved in coal reservoirs as long as a fractured pressure-relief zone is created, which is similar in principle with high drilling on working face and high-level roadway extraction. Based on this principle, Su Xianbo et al. [10−12] and Ma Geng et al. [13] proposed the "virtual reservoir" improved gas extraction technology, which involves fracturing the roof and floor of a coal bed into high-velocity gas producing channels by hydraulic fracturing, which is equivalent to the fractured zones in protective layer mining. It avoids soft coal reservoirs that cannot be stimulated. In addition, the rock stress-sensitivity is much lower than that of soft coal reservoirs. This technology provides an effective means to make breakthrough in soft coal, and recent industrial tests have fully confirmed the feasibility of this process.

In recent years, with the maturity of shale gas reservoir hydraulic fracturing technology [14,15], rapid progress has been made in the theory and technology of coal reservoir fracture network stimulation. Formation mechanisms of various fractures at different levels in hydraulic fracturing were deeply analyzed from the mechanical perspective. Accordingly, fracture network stimulation technology of surrounding beds and coal reservoirs was proposed, which provides a whole new approach for the combined ground and underground efficient gas extraction.

2. Theory of fracture network stimulation

2.1. Concept of surrounding bed mining layer

Surrounding bed mining layers are the roof and floor rocks near coal beds in which fractures of various levels and types can be created through hydraulic fracturing to connect coal beds. They act as pay zones for coal mine gas migration and production, so they were called "virtual reservoirs" earlier [10−13]. The scope of a coal bed connected by fracture network created by hydraulic fracturing of a surrounding bed mining layer is much larger than that of coal reservoir drilling. When coal mine gas desorbs, diffuses and flows to the pay zone, the gas can be rapidly extracted, which is equivalent to establishing a high-speed gas producing channel in the surrounding bed. The surrounding bed mining layer fracturing technology addresses the problem that soft coal reservoir cannot be fractured directly and developed commercially. Meanwhile, the surrounding bed mining layer is far less stress-sensitive than a coal bed, making it possible to obtain commercial productivity from deep coal reservoirs with high geostress.

2.2. Permeability enhancement mechanisms of surrounding bed mining layer fracturing

Multi-stage perforation fracturing, hydraulic-jet multi-stage fracturing, four-variation hydraulic fracturing (variable pumping rate, variable proppant, variable fracturing fluid and variable sand concentration) and some auxiliary measures (tip-screen-out, temporary plugging with balls, etc.) are used in the surrounding bed mining layer fracturing to maximally disturb the in-situ stress field, so as to change the crack initiation and propagation from simple tensile failure to the combined effect of shear, slipping, and leaping, which would create a network of fractures composed of radial tensile fractures, peripheral tensile fractures, shear fractures, etc at different levels. Meanwhile, the brittle particles generated during hydraulic fracturing can prop the fractures themselves, and the wall slippage can also increase fracture volume. In this way, a fracture network system is created in the reservoir by the intersection of natural fractures and artificial fractures of various types and levels, improving the 3D permeability of reservoirs on the whole rather than the conductivity of a few fractures. Meanwhile, the contact area between fractures and reservoir matrix is maximized to minimize flow distance from matrix to fractures and provide high-permeability channels for gas flow. This hydraulic fracturing of reservoir aiming at creating fractures of various types and levels is known as fracture network stimulation technology (Fig. 1). The fracture network stimulation is to solve the problem of whether and how desired fractures can be created.

2.2.1. Radial tensile fracture

During hydraulic fracturing, the weak planes will be pulled apart when the fluid pressure exceeds the minimum horizontal stress and rock tensile strength. Assuming the fracture fluid pressure is equal in all directions, the stress intensity factor at fracture tip [16] is:

$$K_I = \frac{10}{\sqrt{\pi a GSI}} \int_{-a}^{a} p\left(y\right)\sqrt{\frac{a+y}{a-y}}\mathrm{d}y \tag{1}$$

where, K_{I} is stress intensity factor of tensile fracture; $p(y)$ is net pressure of fracture plane; a is the half-fracture length; y is