HOSTED BY
ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Natural Gas Industry B 1 (2014) 197–204
www.elsevier.com/locate/ngib

Research article

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

Ma Geng [a], Su Xianbo [b,*], Lin Haixiao [b], Guo Hongyu [b], Tao Yunqi [a], Liu Xiao [b]

[a] Henan Coal and Chemical Industry Group Co., Ltd., Zhengzhou, Henan 450046, China
[b] School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China

Received 13 May 2014; accepted 25 August 2014
Available online 29 November 2014

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

* Corresponding author.
E-mail address: 1054608403@qq.com (Su XB).
Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2014.11.012

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

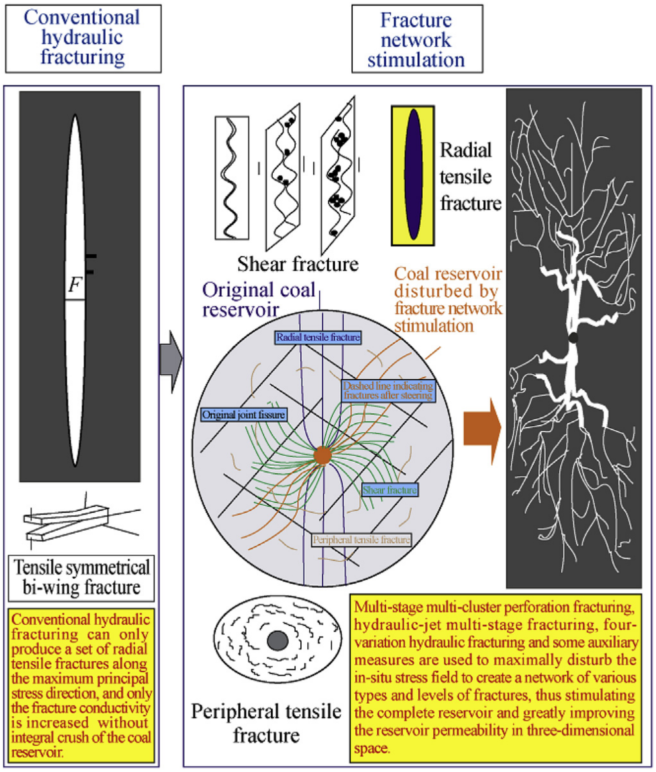

Fig. 1. Schematic diagram of fracture network stimulation.

the distance from any point on the fracture to wellbore center; *GSI* is geological strength index of coal reservoir, which quantitatively reflects the structure and mechanical properties of coal reservoir [17,18], and coal beds with different *GSI* have different stress intensity factors.

When $K_{\mathrm{I}} > K_{\mathrm{I}C}$ ($K_{\mathrm{I}C}$ is fracture toughness of tensile fractures in coal reservoir), tensile fractures will propagate along the maximum principal stress and open along the minimum principal stress and such fractures can be created in any fracturing treatment (Fig. 2).

2.2.2. Shear fracture

Assuming there is a micro-fracture with the length of b in coal reservoir, the shear stress intensity factor [19] can be expressed as (Fig. 2):

$$K_{\mathrm{II}} = \frac{10\tau\sqrt{\pi b}}{\sqrt{GSI}} = \frac{5\sin\alpha a\sqrt{\pi b}\left(\sigma_1^{'} - \sigma_3^{'}\right)}{\sqrt{GSI}} \tag{2}$$

where, K_{II} is the stress intensity factor of shear fracture; σ'_1, σ'_3 are the maximum and minimum effective stresses; α is the included angle of the fracture and minimum effective stress direction (σ'_3); b is the micro fracture length; τ is the fracture plane shear stress.

When $K_{\mathrm{II}} > K_{\mathrm{II}C}$ ($K_{\mathrm{II}C}$ is fracture toughness of shear fractures in coal reservoir), shear fractures will propagate forward, and such fractures can be created in any fracturing treatment theoretically.

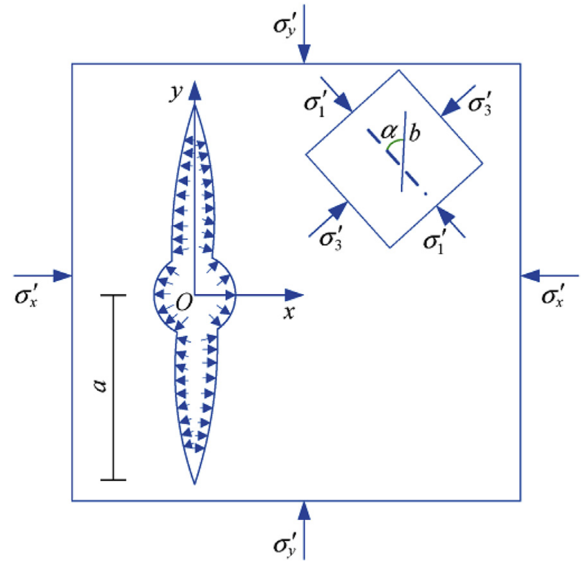

Fig. 2. Schematic diagram of formation mechanisms of radial tensile fractures and shear fractures.

2.2.3. Peripheral tensile fracture

Peripheral tensile fractures almost perpendicular to radial tensile fractures can be created by rapid decrease of pumping rate, pump-off or pressure relief blowout during hydraulic fracturing. These measures will results in rapid pressure relief in wellbore, coal rocks propelled by fluid will displace along the wellbore radial direction, and the displacement gradually decreases outward from borehole wall. Tensile stress will be generated due to the displacement difference between the two sides of weak plane in coal rock, and peripheral tensile fractures are created when the tensile stress exceeds tensile strength of coal rock [20,21] (Fig. 3).

The normal effective stress of fracture and shear stress can be expressed as:

$$\begin{aligned} \sigma_n^{'} &= \frac{1}{2}\left[\left(\sigma_1^{'} + \sigma_3^{'}\right) + \left(\sigma_1^{'} - \sigma_3^{'}\right)\cos 2\alpha\right] \\ \tau &= \frac{1}{2}\left(\sigma_1^{'} - \sigma_3^{'}\right)\sin 2\alpha \end{aligned} \tag{3}$$

where, α is the included angle between the fracture and minimum effective stress direction; τ is shear stress; $\sigma_{\mathrm{n}}^{'}$ the normal stress of fracture.

When $\sigma_{\mathrm{n}}^{'} < 0$, the normal stress of fracture is in tensile state, which will generate normal displacement and breakup. Ignoring the slipping shear resistance friction, $\sigma_\theta^{'}$ at the propagating crackle of fracture tip (r, θ) can be expressed as:

$$\sigma_\theta^{'} = \sqrt{\frac{a}{2r}}\cos\frac{\theta}{2}\left(\sigma_n^{'}\cos^2\frac{\theta}{2} - \frac{3\tau}{2}\sin\theta\right) \tag{4}$$

where, θ is fracture diverting angle; r is propagating crackle length.

Crackles with relatively small length can be regarded as infinite body plane problem. Assuming there is a pair of

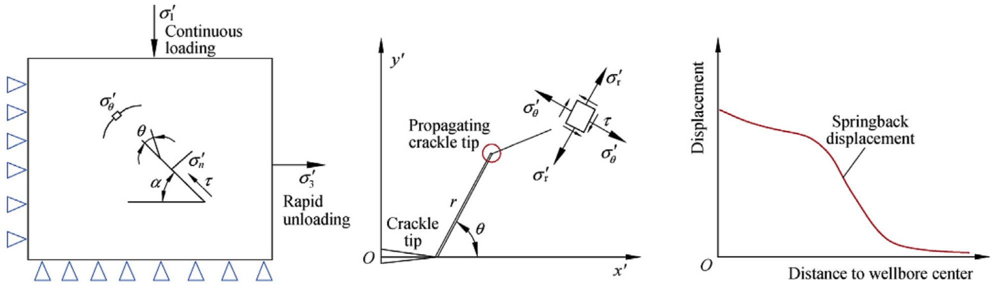

Fig. 3. Schematic diagram of formation mechanism of peripheral tensile fractures.

compressive and tensile stresses at infinity, the stress intensity factor at the tensile crackle tip can be written as:

$$K_I = \frac{10}{\sqrt{GSI}} \lim_{r\to 0}\left[\sigma'_\theta (2\pi r)^{\frac{1}{2}}\right] \tag{5}$$

According to Formulas (4) and (5), the stress intensity factor at the point (r, θ) of propagating fracture is:

$$K_I = \frac{10\sqrt{\pi a}}{\sqrt{GSI}} \cos\frac{\theta}{2}\left(\sigma'_n \cos^2\frac{\theta}{2} - \frac{3}{2}\tau \sin\theta\right) \tag{6}$$

Perform partial derivative for Formula (4) and make it zero, then:

$$2\tau \tan^2\frac{\theta_0}{2} - \sigma'_n \tan\frac{\theta_0}{2} - \tau = 0 \tag{7}$$

where, θ_0 is ripping angle of diverting fracture.

Substituting (θ_0) in Formula (7) into Formula (6), the stress intensity factor of crackle initiation under shear stress can be expressed as:

$$K_I = \frac{10\sqrt{\pi a}}{\sqrt{GSI}} \cos\frac{\theta_0}{2}\left(\sigma'_n \cos^2\frac{\theta_0}{2} - \frac{3}{2}\tau \sin\theta_0\right) \geq K_{Ic} \tag{8}$$

Peripheral tensile fractures can hardly be created in simple injection fracturing, but can be created in the pressure relief stage of pumping rate variation, huff-and-puff or re-fracturing.

2.2.4. Fracture diversion and formation of multi-stage fractures

Variable pumping rate fracturing, multi-stage multi-cluster perforation fracturing and re-fracturing will all cause redistribution of geo-stress. The fractures created in the later stage will propagate in the direction of θ azimuth with the fractures created in the former stage, and these fractures are known as diverted fractures [22,23]. All the fractures created by fracturing will generate induced stress field, which results in the redistribution of geo-stress [24]. The fracture-induced stress at point A is shown in Fig. 4 and expressed as Formula (9)–(12).

$$\sigma'_{x\ \text{induced}} = p\frac{r}{a}\left(\frac{a^2}{r_1 r_2}\right)^{\frac{3}{2}} \sin\theta \sin\frac{3}{2}\left(\theta_1+\theta_2\right) + p\left[\frac{r}{(r_1 r_2)^{\frac{1}{2}}}\cos\left(\theta - \frac{1}{2}\theta_1 - \frac{1}{2}\theta_2\right) - 1\right] \tag{9}$$

$$\sigma'_{y\ \text{induced}} = -p\frac{r}{a}\left(\frac{a^2}{r_1 r_2}\right)^{\frac{3}{2}} \sin\theta \sin\frac{3}{2}\left(\theta_1+\theta_2\right) + p\left[\frac{r}{(r_1 r_2)^{\frac{1}{2}}}\cos\left(\theta - \frac{1}{2}\theta_1 - \frac{1}{2}\theta_2\right) - 1\right] \tag{10}$$

$$\sigma'_{z\ \text{induced}} = \upsilon\left(\sigma'_{x\ \text{induced}} + \sigma'_{y\ \text{induced}}\right) \tag{11}$$

$$\tau_{x\ \text{induced}} = p\frac{r}{a}\left(\frac{a^2}{r_1 r_2}\right)^{\frac{3}{2}} \sin\theta \cos\frac{3}{2}\left(\theta_1+\theta_2\right) \tag{12}$$

where, $\sigma'_{x\ \text{induced}}$ is induced effective stress in x direction; $\sigma'_{y\ \text{induced}}$ is induced effective stress in y direction; P is fluid pressure inside the fracture; r is the distance from point A to coordinate origin; r_1, r_2 are the distances from point A to the two end-points of fracture; θ_1, θ_2 are the inclination angles of the lines across point A and two end-points of fractures and y axis; and v is Poisson ratio.

The ratio of induced stress and net pressure inside the fracture is taken as y-coordinate, and the ratio of the distance to original fractures and half fracture height a are taken as x-coordinate to generate a plot (Fig. 5). It can be seen from the figure that the induced stress varies with the distance from the original fracture. When the distance from the original fracture

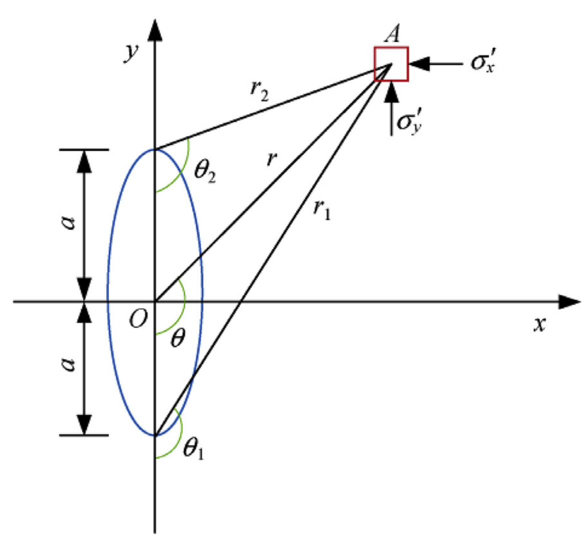

Fig. 4. Schematic diagram of fracture-induced stress field.

exceeds three times that of the half-fracture height, the induced stress is very small and can be neglected [25].

Compound stress field is created through the overlap of fracture induced stress field and in-situ stress field. The complexity of fractures results in the heterogeneity of induced stress field, and thus the complexity of compound stress field. Because of the very heterogeneity of stress fields, fractures of various levels and types are likely to form. Therefore, the primary goal of fracture network stimulation is to maximally disturb the in-situ stress by adjusting fracturing process.

2.2.5. Fracture self-propping

Self-propping effect would generate in shear fractures created during the fracturing of surrounding bed mining layer (Fig. 1). Wall slippage could happen in shear fractures generated during fracturing, resulting in convex points against convex points in two opposite fracture walls and the rise of fracture volume; meanwhile, some large particles created in fracturing retained in fractures would act as proppant to prop fractures.

The above mechanical analysis indicates that the primary goal of fracture network stimulation is to maximally disturb the in-situ stress field. Fractures of various levels and types can be created as long as the stress field is disturbed continuously by hydraulic fracturing. This theoretical analysis has laid foundation for the fracture network stimulation technology.

3. Fracture network stimulation of surrounding beds and coal reservoirs

3.1. Adaptability

3.1.1. Advantages

Surrounding bed mining layer fracture network stimulation, with unique technical advantages, provides a new means to address the two problems in CBM development mentioned above.

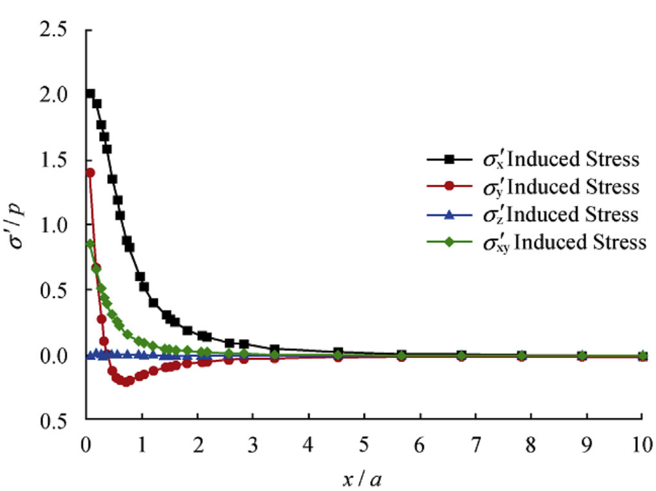

Fig. 5. Variation of fracture-induced stress.

(1) High wellbore stability. Because the mechanical strength of rocks is much greater than that of gas-bearing coal, wellbore instability is greatly improved during drilling, resulting in high-quality of wellbores.
(2) More suitable for fracturing. Except for the shale with strong water-sensitivity, almost all surrounding beds are higher in brittleness index and mechanical strength than coal seam, and thus more likely to form fractures in hydraulic fracturing.
(3) Unlikely fracture closure due to stress-sensitivity. With the going of drainage production the drop of fluid pressure, and the constant rise of effective stress, fractures would gradually close, and proppant would embed in coal beds, resulting in a significant reduction or even complete loss of fracture conductivity. Much high in compressive strength than coal bed, surrounding beds have much better anti-embedment capacity than coal beds, therefore, the unavoidable fracture closure in surrounding beds resulted from stress-sensitivity is much lower than that in coal beds.
(4) Not prone to velocity-sensitivity effect. CBM gas recovery by water drainage must be controlled as a "continuous, slow, and steady" process in order to prevent velocity sensitivity. If a gas well is fractured at coal beds, in the case of the lost control of water drainage gas recovery, coal powder would be produced with fluid, the produced coal powder would either settle in the pocket or in the area near the wellbore (usually in stress concentrated zone), causing severe damage to coal reservoirs. Water drainage gas recovery in wells completed in surrounding beds can significantly decrease the probability of velocity sensitivity, because the surrounding beds are not easily broken to produce rock powder. Even if there is a small amount of rock powder created, it is much lower in inter-particle binding force than that of coal powder, so it is not likely to settle near the wellbore like coal powder in stress-concentrated zones.
(5) Adaptability to coal beds of any structure. For hard coal reservoirs, when the surrounding beds are fractured, the hard coal bed is fractured as well, while for soft coal reservoirs, since the soft coal can not be fractured, only the surrounding beds are fractured.

Gas extraction through fracture network stimulation of surrounding beds with the technical advantages mentioned above provides a whole new technical approach for coal bed methane, and will greatly promote the CBM commercial development in our country.

3.1.2. Limitations of the technology

Although gas extraction through fracture network stimulation of surrounding beds has the above-mentioned technical advantages, it has some limitations too: (1) it is not applicable when the roof and floor surrounding beds are strongly water-sensitive and subject to severe swelling and softening when contacted with water; (2) it is not applicable when the surrounding beds are high in water content or there are other high water-content layers near the surrounding beds.

3.2. Permeability enhancement by fracture network stimulation

Fracture network stimulation of surrounding bed mining layers, applicable to both ground CBM development and underground coal mine gas extraction, is a relatively universal technology. The primary goal of this technology is to maximally generate a network of fractures of various levels and types by using different hydraulic fracturing processes according to coal rock structures, mechanical properties and well-types in order to extract coal mine gas rapidly. For hard coal, both surrounding beds and coal beds are fractured, and gas is produced through one-step diffusion and two-step flow. For soft coal, only surrounding beds are fractured, only extrusion and puncture can be created, and gas is produced through two-step diffusion and one-step flow [12] (Fig. 6). Soft coal can be rushed out through hydraulic jet to achieve pressure-relief, and the corresponding mechanisms are discussed in another paper. Fracture network stimulation of surrounding beds can be realized by the following technical measures.

3.2.1. Four-variation hydraulic fracturing

Four-variation hydraulic fracturing is an effective way to achieve fracture network stimulation through changing the pumping rate, sand concentration, proppant and fracturing fluid.

3.2.1.1. Variable pumping rate fracturing. Variable pumping rate fracturing involves changing the pumping rate from low to high repeatedly to disturb the reservoir during fracturing, and low pumping rate here could be pump-off. Radial tensile fractures are created with the increase of pumping rate and pressure; while peripheral fractures are created with pressure relief in coal reservoirs in the case of pumping rate decrease or pump-off. Meanwhile, wall slippage could happen in shear fractures and radial tensile fractures produced in early stage to increase fracture volume and achieve fracture self-prop. In-situ stress field is disturbed continuously and compound stress field is generated through repeated variable pumping rate injection, which can lead to fracture diversion, and in turn the formation of a network of fractures of various levels and types. Variable pumping rate fracturing is the core in the four-variation fracturing.

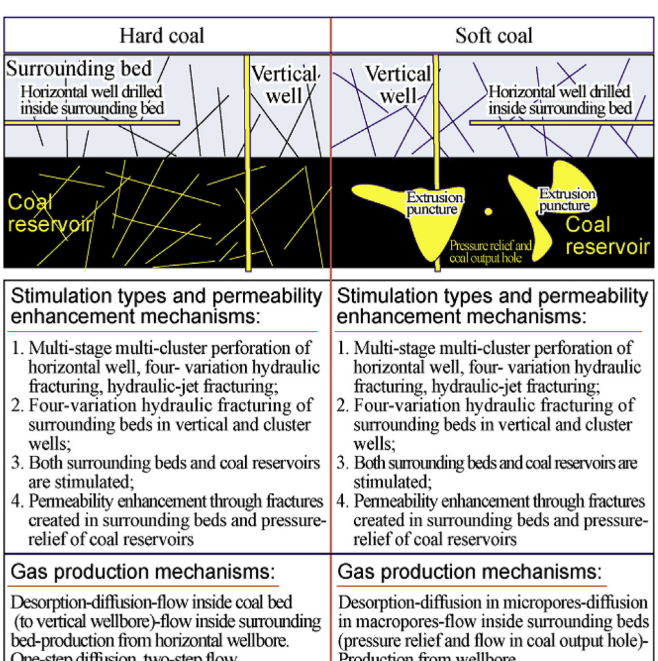

Fig. 6. Schematic of fracture network stimulation technology.

3.2.1.2. Variable sand concentration. Variable sand concentration fracturing is complementary to variable pumping rate fracturing. Proppant is added at large pumping rate stage to form slug, proppant is not added at small pumping rate stage to establish isolation, and room-pillar prop is established. This technology is also named as "channel fracturing" by some scholars [26,27]. The propped fracture conductivity depends on proppant roundness, sphericity, compressive strength and crushing ratio. Quartz sand, low in compressive strength and high in crushing ratio, can not keep the conductivity of fractures stable for a long term. However, the propped room pillars can be created by proppant in variable sand concentration channel fracturing, gas can rapidly transport as long as the channels between room-pillars have high conductivity rather than room pillars themselves. Therefore, channel fracturing has low enough requirement for proppant to establish room pillars.

Variable sand concentration fracturing is usually used jointly with fracture tip-screen-out, temporary plugging with balls and other auxiliary measures, to achieve better fracturing result. In addition, enough rock strength is necessary in variable sand concentration fracturing to prevent the created room pillars from being crushed [28], which is just the advantage of surrounding bed mining layers.

3.2.1.3. Variable fracturing fluid. Variable fracturing fluid is to make full use of fracturing fluid to achieve effective prop of fractures of various types and levels. Usually, inexpensive active water is used as prepad fluid to achieve a multiplier effect, and fracturing fluids of high viscosity and high sand-carrying capacity such as expensive guar gel are used as sand-carrying fluid to achieve effective prop of fractures. Variable fracturing fluid stimulation is the so-called compound fracturing.

3.2.1.4. Variable proppant. Variable proppant involves changing proppant size and proppant type. (1) Variable proppant size: A certain amount of fine sand is usually added in prepad fluid to plug filtration in large-scale fractures, rub fracture walls and prop micro-fractures; medium sand added in sand-carrying fluid is the dominated proppant to support flow channels; coarse sand is added finally to establish high-permeability channels near wellbores. (2) Variable proppant type: Variable proppant type is closely related to variable fracturing fluid. Inexpensive active water is usually taken as prepad fluid with fine sand to create fractures. Wood proppant (such as walnut shell) or ultra-low density ceramsite should be used if active water is taken as sand-carrying fluid. High compressive strength proppant (such as ceramsite) should be added if high-viscosity fracturing fluids such as guar gum are taken as sand-carrying fluid. Except for fracturing treatment of shallow coal reservoirs with low closure stress or variable sand concentration fracturing treatment, it is not generally recommended to use quartz sand as proppant.

The “four variations” in four-variation fracturing are complimentary. According to the specific reservoir characteristics of a block or a well, fracturing must be designed accordingly to the actual conditions for every block and special measures must be taken for every well, thus reaching the goal of fracture network stimulation.

3.2.2. Fracture network stimulation for ground CBM development

Based on the above-mentioned mechanical mechanisms of fracture creation and four-variation fracturing technology, surrounding bed fracture network stimulation can be used in coal reservoirs of any structures, and has distinctive leading edges in soft coal especially.

3.2.2.1. Fracture network stimulation of surrounding beds in horizontal wells. Horizontal wells can be drilled in the roof or floor surrounding beds at a certain distance from the coal bed (Fig. 6). The fracturing stage division is determined by coal structures, mechanical properties, stimulated reservoir volume, geo-stress and fracturing capacity, and the length of each stage is generally no more than 100 m. Multi-cluster spirals or oriented perforations can be adopted, and shot density is dependent on fracturing demand. Packers can be used to isolate each stage mechanically or hydraulic-jet multi-stage fracturing can be used to isolate them automatically. Active water or slick water can be taken as fracturing fluid in shallow coal reservoirs with low geo-stress. Guar gum or clean fracturing fluids combined with low-temperature mandatory breaker must be used in deep and high geo-stress coal reservoirs, and self-reproducing nitrogen had better be added in the fracturing fluid to ensure complete gel-breaking and rapid flowback. Proppant is dominated by medium size sand, with coarse sand in tailing fluid, and fine sand in prepad fluid. If the four-variation fracturing treatment is taken, the pumping rate and injected sand volume will depend on coal rock structures and stimulated reservoir volume.

Fracture diversion is achieved by stress disturbance between clusters and between stages in horizontal well multi-cluster perforation multi-stage fracturing, which, together with “four-variation” fracturing, can reach the goal of creating a network of fractures of various types and levels, and thus fracture network stimulation is realized in the end. In the U-type wellbore in Zhongma Village Mine of Henan Coal Group, the horizontal section is placed in the roof surrounding bed 5 m above the coal bed, the horizontal section around 300 m long was fractured by hydraulic-jet multi-stage fracturing, to extract gas through the mining layer in the surrounding beds. The fracturing was relatively small in scale due to the conflict with coal mine underground engineering, but the well had a gas production rate of 2300 m^3/d, the first ground well that extracts gas through surrounding bed stimulation.

3.2.2.2. Fracture network stimulation for vertical and cluster wells. The fracture network stimulation of surrounding beds in vertical and cluster wells are usually done by the four-variation fracturing. When all coal layers are soft coal, the surrounding beds will only be fractured by the four-variation fracturing to realize the fracture network stimulation. When there are hard coal layers in a coal reservoir, the hard coal layers will be fractured together with the surrounding beds. If there are brittle dirt bands in a coal reservoir, the brittle dirt bands are also fractured. Coal layers are firstly fractured, then mining layers in surrounding beds by the four-variation fracturing assisted by tip-screen-out and temporary ball plugging. The fracturing fluid, proppant, pumping rate, etc. are selected according to the same principle as that for horizontal wells. Uneven perforation similar to multi-stage multi-cluster perforation in horizontal wells can be tested, and higher shot density should be taken in coal layers to facilitate stress disturbance.

Fracture network stimulation of mining layers in surrounding beds has been applied successfully in vertical wells in Gujiao, Shanxi. There developed two coal layers of 1−3 m thick in this region, the two layers of fragmented coal are 5−10 m apart, with silty mudstone and siltstone in between, and gas content of 10−15 m^3/t. The two wells in which the coal beds and surrounding beds in between were fractured together have a steady production of 1600 m^3/d; while the well in which only the coal beds were fractured has a gas production rate of only 150 m^3/d. This test fully demonstrates the technical advantages of fracture network stimulation of mining layers in surrounding beds.

3.2.3. Fracture network stimulation for underground coal mine gas extraction

In 2004, the author proposed the introduction of ground CBM development fracturing to underground coal mines [29]. Underground surrounding beds − coal reservoir hydraulic fracturing was actually implemented in 2008, and is industrializing with strong vitality.

Surrounding beds and coal beds can be fractured as a whole by huff-and-puff fracturing, re-fracturing, hydraulic-jet fracturing, etc to realize fracture network stimulation. The fracturing process is selected according to coal structures and mechanical properties [30]. With remarkable permeability enhancement effect and low cost, fracture network stimulation of mining layers in surrounding beds and coal beds, a new way to extract coal mine gas underground, is popularized gradually in mines with very high coal mine gas outburst of Henan, Chongqing, Guizhou, Anhui, Shanxi, etc.

4. Conclusions

Considering that the current hydraulic fracturing processes cannot meet the requirements of CBM commercial development in soft coal reservoirs and deep coal reservoirs with high geo-stress, a fracture network stimulation technology of surrounding beds and coal beds is proposed in this paper. Different hydraulic fracturing processes are applied in this technology to stimulate surrounding beds − coal beds to create a network of fractures of various types and levels, and achieve large-scale gas extraction in the end. Mechanical analysis indicates that hydraulic fracturing can produce fractures of various types and levels, including radial tensile fractures, peripheral tensile fractures, and shear fractures, etc. After presenting the applicability and limitations of the fracture network stimulation of surrounding bed mining layers, four technical approaches to realizing fracture network stimulation, including the four-variation fracturing, multi-stage fracturing through multi-cluster perforations in horizontal wells, hydraulic-jet fracturing and some auxiliary measures are described. The primary goal of this technology is to create fractures of various types and levels by disturbing the in-situ stress field and improve gas extraction efficiency significantly. Successful tests of ground and underground gas extraction has preliminarily established a set of fracture network stimulation technical system for surrounding beds and coal beds up and down wells. This technology addresses the two problems in coal bed methane development: soft coal reservoirs which can't be fractured, and low gas production of deep coal reservoirs with high geo-stress. The popularization of this technology will promote CBM commercial development in our country and provide a new way for coal mine gas management.

Acknowledgments

Fund project: “Research on the formation mechanism of coal seam methane” (No. 41002047 and No. 40972109) supported by State Natural Sciences Foundation.

References

[1] Karacan CÖ, Ruiz FA, Cotè M, et al. Coal mine methane: a review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. Int J Coal Geol 2011;86(2/3):121−56.
[2] Gunter WD, Gentzis T, Rottenfusser BA, et al. Deep coalbed methane in Alberta, Canada: a fuel resource with the potential of zero greenhouse gas emissions. Energy Convers Manag 1997;38(S1):217−22.
[3] Scott S, Anderson B, Crosdale P, et al. Coal petrology and coal seam gas contents of the Walloon subgroup-Surat Basin, Queensland, Australia. Int J Coal Geol 2007;70(1/3):209−22.
[4] Ian P. Coalbed methane completions: a world view. Int J Coal Geol 2010;82(3/4):184−95.
[5] Guo Hongyu, Su Xianbo, Xia Daping, et al. Relationship of the permeability and geological strength index (GSI) of coal reservoir and its significance. J China Coal Soc 2010;35(8):1319−22.
[6] Chen Zuo, Meng Xiangyan, Du Changhong, et al. Fracturing techniques of tight sand reservoirs with abnormal high earth stress. Nat Gas Ind 2005;25(12):92−4.
[7] State Administration of Work Safety. AQ1027-2006 code for coal mine gas drainage. 2006.
[8] Yuan Liang, Guo Hua, Shen Baotang, et al. Circular overlying zone at long wall panel for efficient methane capture of multiple coal seams with low permeability. J China Coal Soc 2011;36(3):357−65.
[9] Qian Minggao, Xu Jialin. Study on the “O-shape” circle distribution characteristics of mining induced fractures in the overlaying strata. J China Coal Soc 1998;23(5):20−3.
[10] Su Xianbo, Tang Youyi. Coalbed methane drainage technology in Henan Province. In: Proceedings of the 1999 international symposium on mining science and technology; 29−31 August 1999. Beijing, China.
[11] Su Xianbo, Tang Youyi, Sheng Jianhai. On three proposals of the coalbed methane development in Henan Province. J Jiaozuo Inst Technol Nat Sci Ed 1998;17(6):406−8.
[12] Su Xianbo, Chen Jiangfeng, Sun Junmin, et al. Coalbed gas geology and exploration. Beijing: Science Press; 2001. p. 192−4.
[13] Ma Geng, Gong Chunsheng. Probing into gas drainage technology by virtual reservoir. Saf Coal Mines 2009;40(5):94−5.
[14] Wu Ji, Xu Yun, Liu Yuzhang, et al. The current situation of stimulated reservoir volume for shale in U.S. and its inspiration to China. Oil Drill Prod Technol 2011;33(2):1−7.
[15] Mayerhofer MJ, Lolon EP, Warpinski NR, et al. What is stimulated rock volume. In: Paper 119890 presented at the SPE shale Gas production conference; 16−18 November 2008. Fort Worth, Texas, USA.
[16] Zhang Guangqing, Chen Mian, Zhao Yanbo. Study on initiation and propagation mechanism of fractures in oriented perforation of new wells. Acta Pet Sin 2008;29(1):116−9.
[17] Hoek E, Brown ET. Practical estimates of rock mass strength. Int J Rock Mech Min Sci 1997;34(8):1165−86.
[18] Hoek E. Practical rock engineering. Translated by Liu Fengshou, Cui Zhifang, Wang Xuechao, et al. Zhengzhou: Yellow River Water Resources Press; 2002.
[19] Deng Huafeng, Li Jianlin, Liu Jie, et al. Research on propagation of compression shear fracture in rocks considering fissure water pressure. Rock Soil Mech 2011;32(S1):297−302.
[20] Huang Da, Huang Runqiu. Physical model test on deformation failure and crack propagation evolvement of fissured rocks under unloading. Chin J Rock Mech Eng 2010;29(3):502−12.
[21] Huang Da. Study on unloading deformation mechanism and stability of excavating surrounding rock mass of large underground caverns Chengdu. Chengdu University of Technology; 2007.
[22] Zhao Lei. Refracturing technology. Dongying: China University of Petroleum Press; 2008.
[23] Chinese Aeronautical Research Institute. Manual of stress intensity factor. Beijing: Science Press; 1981. p. 426−8.
[24] Liu Hong, Yi Jun, Li Wenhua, et al. Mathematical model of 3D induced stress field in refracturing gas well. Oil Drill Prod Technol 2004;26(2):57−61.
[25] Liu Lifeng, Zhang Shicheng. Net fracturing by changing the surrounding in-situ stress in shale reservoirs. Oil Drill Prod Technol 2011;33(4):71−4.
[26] Zhong Sen, Ren Shan, Huang Yuzhong, et al. Research and application of channel fracturing technique in foreign oil and gas fields. Sino-Global Energy 2012;17(6):39−42.
[27] Soliman MY, Augustine J. In: Fracturing design aimed at enhancing fracture complexity||SPEEUROPEC/EAGE annual conference and exhibition; 14−17 June 2010. Barcelona, Spain.
[28] Emmanuel D, Matt G, Matt M, et al. Open channel fracturing-A fast track to production. Oilfield Rev 2011;23(3):4−17.
[29] Henan Polytechnic University. Gas drainage technology of permeability improvement by downhole hydraulic fracturing underground coalmine: China. 200810230940.4. 2008-11-18.
[30] Guo Hongyu. Gas drainage theory and technology in underground coal mine based on hydraulic fracturing. Jiaozuo: Henan Polytechnic University; 2011.