First International Symposium on Mine Safety Science and Engineering

Theoretical Analysis and Practical Study on Reasonable Water Pressure of Hydro-fracturing

Ye Qing\textsuperscript{a,b}, Jia Zhenzen\textsuperscript{a}, Lin Baiquan\textsuperscript{c}, Li Jianxin\textsuperscript{b}, Li Guoqi\textsuperscript{b} \textsuperscript{a*}

\textsuperscript{a}Hunan Province Key Laboratory of Safety Mining and Technology of Coal Mine, Hunan University of Science and Technology, Xiangtan, Hunan 411201, China;
\textsuperscript{b}YIMA Coal Industry Group Co, Ltd, Henan 472300 China;
\textsuperscript{c}China University of Mining and Technology, Xuzhou, Jiangsu 221008, China.

Abstract

The hydro-fracturing technology is the depressurization antireflection elimination outburst technology for the low permeability outburst coal seam with high methane. At present, the mechanism of the depressurization antireflection elimination outburst is sufficiently mastered and the application effectiveness of field engineering also is well, but how to determine hydro-fracturing parameters is not systematically described, especially the reasonable water pressure. Based on the hydro-fracturing mechanism and process, the reasonable water pressure is theoretically analyzed, and then the pressure parameter of hydro-fracturing applied in the low permeability outburst coal seam with high methane is obtained, finally the reasonable pressure formula of water injection is obtained. The application test results of field engineering shows that there is the difference between the theoretical analysis result and the pressure in field engineering test, namely, the theoretical analysis pressure is lower than the pressure in field engineering test.

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and/or peer-review under responsibility of China Academy of Safety Science and Technology, China University of Mining and Technology (Beijing), McGill University and University of Wollongong.

Keywords: hydro-fracturing; reasonable water pressure; fracturing mechanism; fracturing technique.

1. Induction

From the current research status of methane disaster control, the key problem of coal seam methane drainage is how to improve the permeability of coal seam. From safety and application effect, the hydro-fracturing can well solve the problem of the low permeability of coal seam. Although the hydro-fracturing technology was well understand by people\cite{1,2}, the analysis on the reasonable water injection

\* Corresponding author. Tel.: +086-0731-58290040; fax: +086-0731-58290040.
\textit{E-mail address:} cumtyeqing@126.com.
parameters (especially water injection pressure) are not accurate. If the water injection pressure is too low, the coal seam can not be effectively fractured, which can not make coal produce obvious change, so in short time, the hydro-fracturing with low water injection pressure can not reach the effect of depressurization antireflection elimination outburst. If the water injection pressure is too high and mismatch between borehole sealing length and fracturing pressure, the comprehensive function of the geostatic stress and water injection pressure makes coal roadway produce quick deformation and move toward roadway(mining space), which can result in outburst. So the hydro-fracturing technology with the reasonable water injection pressure can quickly fracture coal and change the coal pore structure, in finally, the methane can be drained by coal seam drainage-hole and the elimination outburst can be reached. In this paper, based on the hydro-fracturing mechanism, the reasonable water injection pressure is theoretically analyzed and tested in field engineering, in finally; the reasonable water injection pressure is obtained. The determination of the reasonable water pressure is important to improve the permeability of coal seam and drainage effect.
2. Analysis on hydro-fracturing mechanism and process

2.1. Analysis on hydro-fracturing mechanism

The basic principle of hydro-fracturing is that the high pressure water (fracturing fluid) is injected into the original crack(fracture) and the crack brought by fracturing, and overcomes the coals’ minimum principal stress and the fracture pressure, widens, stretches and communicates the cracks, increases the number of intersection fractures and increases the open degree of the single fracture surface, which can produce more artificial fractures and cracks, thus increase the permeability of coal seam\textsuperscript{[2-4]}, at the same time, the high pressure water entering into the coal fractures can drive methane in coal, which can make free methane and adsorption methane move toward drainage-boreholes, and then increase methane drainage quantity. The hydro-fracturing mechanism includes two aspects of fracture generation and fracture extension, fracture generation is controlled by many factors, of which the factors are usually confirmed by test.

The hydro-fracturing can change the coals’ mechanical properties obviously, reduce coals’ flexibility and strength, increase the coals’ plasticity, and then can obviously change stress distribution in front of the workface, and make the stress concentration belt enter into the deep coal, which can alleviate methane outburst. Because the high pressure water can drive methane in coal, decrease the methane content and reduce methane emission, and then reduce the number of methane exceed-limit in the mining face and upper corner. At the same time, the hydro-fracturing can wet the coal and reduce the coal dust during the coal mining process.

2.2. Analysis on hydro-fracturing process

The hydro-fracturing is the process of water injection wetting the coal, fracturing broken coal and driving the methane in coal. In the early period, the water injection pressure and water injection flow take on linear rise with the injection time, and then water injection pressure take on reverse change with flow, which shows that water with pressure enters into coal fractures through borehole and overcomes fracture resistance, after water filling with existing fractures, the water flow is hampered. For the coals’ low permeability, the flow reduces, the pressure increases and potential energy is saved. When the saved potential energy can break coal and form new fractures, the water with pressure enters into new fractures, the saved potential energy translates into the kinetic energy, so the pressure reduces and flow increases. When the water (fracturing fluid) with coal slime blocks up the fractures, the coal permeability reduces, so the flow reduces and the pressure increases. The reasonable water injection pressure is an important parameter for the fracturing effect.
3. The theoretical analysis on reasonable water injection pressure

The shape of fractures and pore in coal is irregular, in order to analyze the pressure conveniently, the shape of fractures and pore are assumed as round, which is shown in fig.1. A is assumed as a arbitrary point in round, L is tangent line through A point, the radius is R, methane pressures is $P_0$, radial stress is $\sigma_r$, tangential stress $\sigma_\beta$, the angle in A point is $\alpha$, shear stress in A point is $\tau$.

Boundary conditions

\[
\begin{align*}
\left( \sigma_r \right)_{r=a} &= P_0 \\
\left( \tau_\beta \right)_{r=a} &= 0 \\
\left( \sigma_r \right)_{r=R} &= (\sigma_1 + \sigma_2) / 2 + (\sigma_1 - \sigma_2) \cos 2\alpha / 2 \\
\left( \sigma_\beta \right)_{r=R} &= (\sigma_1 + \sigma_2) / 2 - (\sigma_1 - \sigma_2) \cos 2\alpha / 2 \\
\left( \tau_\beta \right)_{r=R} &= (\sigma_2 - \sigma_1) \sin 2\alpha / 2 
\end{align*}
\]

(1)

According to the boundary conditions, assuming the stress function as $\varphi = f(r) \cos 2\alpha + g(r)$, let the stress function introduce into compatible equation, it can be obtained as follows.

\[
\left( \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \alpha^2} \right) \varphi = 0
\]

(2)

By elastic mechanics principle, the stress components of the coal around fracture and pore can be deduced as follows:
\begin{align}
\begin{cases}
\sigma_r = 0.5(\sigma_1 - \sigma_2)(1 - 4\frac{a^2}{r^2} + 3\frac{a^4}{r^4})\cos 2\alpha + \frac{P_0 a^2}{r^2} + 0.5(\sigma_1 + \sigma_2)(1 - \frac{a^2}{r^2}) \\
\sigma_\beta = -0.5(\sigma_1 - \sigma_2)(1 + 3\frac{a^4}{r^4})\cos 2\alpha - \frac{P_0 a^2}{r^2} + 0.5(\sigma_1 + \sigma_2)(1 + \frac{a^2}{r^2}) \\
\tau_{r\beta} = -0.5(\sigma_1 - \sigma_2)(1 + 2\frac{a^2}{r^2} - 3\frac{a^4}{r^4})\sin 2\alpha
\end{cases}
\tag{3}
\end{align}

Under the action of methane pressure and geostatic stress, the radial stress of the pores’ internal surface turns into pressure, and the tangential stress turns into tensile stress. If the radial stress is more than the coal’s compressive strength, the shear failure will be occurred in the coal borehole wall; If tangential stress is more than coal’s tensile strength, the extension damage will be happen in pore. In this time, the water injection pressure is the initial pressure of fracture collapse.

From the rock mechanics, it can be obtained that the stress concentration coefficient about the pore is the largest, when \( r = a \), pore pressure is the largest.

\begin{align}
\begin{cases}
\sigma_r = P_0 \\
\sigma_\beta = -2(\sigma_1 - \sigma_2)\cos 2\alpha - P_0 + (\sigma_1 + \sigma_2) \\
\tau_{r\beta} = 0
\end{cases}
\tag{4}
\end{align}

From \( \frac{\partial \sigma_\alpha}{\partial \alpha} = 0 \), \( \alpha \) is the constant.

When \( \alpha \) is \( 0^\circ \)
\begin{align}
\begin{cases}
\sigma_r = P_0 \\
\sigma_\beta = -\sigma_1 - P_0 + 3\sigma_2
\end{cases}
\tag{5}
\end{align}

When \( \alpha \) is \( 90^\circ \)
\begin{align}
\begin{cases}
\sigma_r = P_0 \\
\sigma_\beta = 3\sigma_1 - P_0 - \sigma_2
\end{cases}
\tag{6}
\end{align}

If the fracture need to be produced, \( \sigma_\beta \) must be less than zero and \( |\sigma_\beta| > \text{tensile strength } |R_1| \).

When the fracture produces in left and right of roadway, \( \alpha \) is \( 0^\circ \), namely when \( \alpha \) is \( 0^\circ \)
\begin{align}
\begin{cases}
\sigma_r = P_0 \\
P_0 - 3\sigma_2 + \sigma_1 < |R_1|
\end{cases}
\tag{7}
\end{align}

When the fracture produces in top and bottom of roadway, \( \alpha \) is \( 90^\circ \), namely when \( \alpha \) is \( 90^\circ \)
\begin{align}
\begin{cases}
\sigma_r = P_0 \\
P_0 + \sigma_2 - 3\sigma_1 < |R_1|
\end{cases}
\tag{8}
\end{align}

So the water injection pressure \( P_{\text{zhu}} \) Equal to \( P_0 \) plus \( P_{\text{gas}} \), namely \( P_{\text{zhu}} = P_0 + P_{\text{gas}} \).

Considering the pressure loss of pipeline in the water injection process, \( P_{\text{zhu}} = P_0 + P_{\text{gas}} + P_{\text{loss}} \).
4. Analysis on the hydro-fracturing technique and engineering

The hydro-fracturing technology includes three aspects: the borehole construction technique, hydro-fracturing technique of coal seam and technology protection measures. In this engineering, a certain number of fracturing borehole and drainage borehole (observation borehole) in coal seam are constructed, after sealing, the hydro-fracturing is carried out. Only the hydro-fracturing technique and process is analyzed in paper.

4.1. The condition of test coal seam

YiAn coal mine is located in the Zheng village of Xinan County, the length of the mine field is about 6.3 km, the tendency width is about 5.5 km, the area is about 28.744 km². The coal strata belongs to carboniferous strata and permian system, the minable coal seams are 2₁ coal seam and 2₂ coal seam, 2₁ coal seam is minable seam of whole area, 2₂ coal seam is minable seam of locality, the average thickness of the minable coal seam is 4.84m, the coal seam methane content is 12.61m³/t, the methane pressure is 1.37MPa, the coal seam firmness coefficient f is 0.2 or so, the coal damage type belongs to V and IV, the coal seam belongs to the outburst coal seam. Because YiAn mine’s coal seam thickness is large, the development is complete and the destruction structure is serious, the existing methane treatment technology and equipment more and more can not meet the requirements, the main problems are low permeability, soft coal seam and the difficulty of the existing technology. So the hydro-fracturing test is carried out, the test place is located in rubber belt roadway of FD003 workface in the YiAn coal mine, the length of rubber belt roadway is 812 m.

4.2. Analysis on the hydro-fracturing technique parameters

As showed in fig.2, the hydro-fracturing system consists of fracturing pump, the pressure gauge, water tank and special borehole packer. The fracturing pump is the YL40/315 type piston fracturing pump with rated pressure of 40MPa and maximum displacement of 1.2m³/min. For convenience of operation and control, a pressure gauge, water meter and pressure relief valve and other accessories are installed in
fracturing pump, the water tank is the special underground fracturing spare water tank, many water tanks are paralleled. The high pressure pipeline is chosen as high pressure rubber tube with diameter of 2 inch, the high quality seamless steel tube is adopted in borehole. The borehole sealing-packer and high pressure rubber tube is connected by the rapid adapter connector.

5. Field test of hydro-fracturing technology

5.1. hydro-fracturing parameters

1) Borehole arrangement. The borehole parameters is layout as follows: ①the NO.1 fracturing borehole is arranged in the tenth drilling field of rubber belt roadway of FD003 workface in the YiAn coal mine, the NO.1 observation borehole is installed in 15 meters distance from the left of the NO.1 fracturing borehole; the NO.2 observation borehole is installed in 20 meters distance from the right of the NO.1 fracturing borehole. The depth of the NO.1 fracturing borehole is 100 meters, the depth of the NO.1 observation borehole and the NO.2 observation borehole is 70m. ②the NO.1 observation borehole and the NO.2 observation borehole are earliest constructed, when the construction is over, the orifice plate flow-meter is installed in the observation borehole, the methane in coal seam is drained from the observation borehole. ③when the time of methane drainage in the NO.1 observation borehole and the NO.2 observation borehole are more one work-time, the NO.1 fracturing borehole is constructed and hydro-fracturing is tested. By observing the change of drainage parameters in NO.1 observation borehole and the NO.2 observation borehole, the hydro-fracturing radius can be obtained.

2) The water injection pressure. According to the geostatic stress, the methane pressure and the stress distribution law, the water injection pressure of hydro-fracturing is 8～30MPa.

3) The fracturing time. The fracturing time is closely related with water injection pressure and water injection parameters. When the water injection pressure and flow velocity change, the water injection time also changes in the same condition. During the water injection, the coal gradually becomes damage by fracturing, all the pores and fractures gradually communicate, the high pressure water flows in communicated fractures, so the water injection pressure and water injection flow also gradually change. The water injection time can be obtained by changes of pressure and flow in water injection process.

5.2. Hydro-fracturing processes

During the fracturing process, the dynamic pressure water injection is adopted, the time of all the fracturing process is about 60min, the velocity is 2Mpa/5min. when the pump pressure arrives at the design pressure, the pressure rapidly decrease after a stable time, even if the pump pressure is continued to increase, the increase of fracturing pressure is not obviously (or when roadway methane concentration obviously increase), which can show the roadway begins to produce the fractures, at this time, the fracturing process is over. During the fracturing process, the continuous record of water injection pressure and flow is needed to be written. According to the field condition, the fracturing parameters are needed to be adjusted.

5.3. pressure observation of hydro-fracturing

The fracturing is carried out two hour in the NO.1 fracturing borehole, the highest water injection pressure is 23Mpa, and the total water injection quantity is 33.7m³. After fracturing, the phenomena are produced as follows: ① there are the signs that roadway wall of 20 mm near to the fracturing borehole moves toward roadway. ② during the fracturing process, the methane drainage quantity rises obviously.
After 20 min of fracturing, the methane concentration gradually begins to rise from 0.1% to 0.17%. From the drainage borehole methane concentration, drainage borehole methane concentration is 0.1% ~ 0.6% before fracturing, and the average is 0.2%; After fracturing, the drainage borehole methane concentration is 0.42% ~ 37.4%, and the average is 16%; the drainage borehole methane concentration after fracturing is more than 80 times of concentration before fracturing. From the drainage borehole methane net quantity, before fracturing, the drainage borehole methane net quantity is 0.0005% ~ 0.1396%; After fracturing, the drainage borehole methane net quantity is 0.0077% ~ 1.2856%, the drainage borehole methane net quantity after fracturing is more than 60 times of concentration before fracturing.

According to the different test locations, the water injection pressure obtained from test is very close to theoretical pressure, but the theoretical pressure is less than the actual test stress. The reason may be that the measured methane pressure of coal seam and calculation loss pressure are smaller than the actual pressures, the physical mechanical parameters of the coal seam exist differently.

6. Conclusions

By the theoretical analysis and the test of the water injection pressure of hydro-fracturing, the conclusions are as follows:

1. The hydro-fracturing can make the elasticity and intensity decreases, plasticity increases, the hydro-fracturing can make the stress distribution bring the fundamental change, and can make the stress concentration belt go toward the deep coal, which can eliminate or reduce the risk of outburst. The hydro-fracturing measures can drive the methane of the coal seam, at the same time, the hydro-fracturing can wet the coal, which can reduce the coal-dust.

2. The theoretical pressure value of water injection is obtained as $P_{zhu} = P_0 + P_{gas} + P_{loss}$.

3. The actual water injection pressure is higher than the pressure of theoretical water injection, the actual water injection pressure changes with the changes of coal seam properties. The reason may be that the measured methane pressure of coal seam and calculation loss pressure are smaller than the actual pressures, the physical mechanical parameters of the coal seam exist differently.

4. During the fracturing process, methane drainage quantity rise obviously, the drainage borehole methane concentration after fracturing is more than 80 times of the concentration before fracturing; drainage borehole methane net quantity after fracturing is more than 60 times of the net quantity before fracturing.

Acknowledgements

This work was Supported by the National Natural Science Foundation of China (51004048, 51074161), the Research Fund of State Key Laboratory of Coal Resources and Safe Mining, CUMT(09KF05), the Post-Doctoral Science Foundation of China (20100470998), the Scientific Research Fund of Hunan Provincial Education Department(09C409), the State Key Base Development Plan(2011CB201205). Their support is acknowledged with thanks.

References

[1]. Zhou Lunmin. Trials on hydro-fracturing technology for enhancement of permeability of outburst coal seam[J].China coal bed methane,2009V6N3:34-39.

[2]. Zhang Guohua. Study of Induce-crack Mechanics and Cranny’s Development Process about Hydraulic Fracture in Mining-coal Bed[D]. Liaoning University of Engineering Technology,2003.12.
[3] Liu Xianlin. Research and application of explain technology and real-time monitoring of hydraulic fracturing and [D]. South West Petroleum University, 2003.10.

[4] Luo Tianyu. Study on the mechanism of multiple fractures in hydraulic fracturing [D]. South West Petroleum University, 2006.5.

[5] Lian Zhilong. A simulation study of hydraulic fracturing propagation with a solid-fluid coupling model [D]. University of Science and Technology of China, 2007.5.

[6] Chen Xiaokui. Research on effects of hydraulic fracturing on gas pressure [J]. Energy Technology and Management, 2010, 6:4-6.

[7] LV You-chang. Application the hydraulic fracturing technology in the high pressure and low permeability mine [J]. Journal of Chongqing University, 2010, 33(7):102-107.

[8] Zhang-Feng. The Mechanism and Parameters-optimization of Injection Fracture Pressure Propagation for Low Permeability Oil Field [D]. China University Of Petroleum, 2009.

[9] Chen Yuanjiang. The improvement measures and influence factors analysis on coal bed permeability under water injection [J]. SAFETY IN COAL MINES, 1997, 12:15-18.

[10] AI Can-biao, JIA Xian-zong. Test of Hydraulic Fracture and Its Effect Analysis in Xinyi coal mine [J]. Coal Mining Technology, 2010, 4:109-117.