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Numerical Simulation Study on the Coal Seam Pulse Water Infusion

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Abstract: In the process of coal seam pulse water infusion, liquid-solid coupling effect exists in coal seam between the stress field and seepage field. Based on the basic principle of liquid-solid coupling, the dynamic liquid-solid coupling effect of stress and seepage field during coal seam pulse water infusion is simulated through secondary development of ABAQUS software, during this process the mathematical model of the strain accumulation model due to the periodic changes of pulse water pressure is embedded in SOIL module of ABAQUS software. The law of different parameters of pulse water infusion on the permeability of coal around the infusion hole is gotten. Numerical simulation results show that, during the process of coal seam high pressure pulse water infusion, the stress field and flow field are mutual influence and mutual restriction. The coupling of the stress and flow field have impact on the physical and mechanical properties of coal in front of the working face, these factors promote each other and preventing coal and gas outburst effectively. The permeability of coal increase significantly with the water infusion time prolong under constant water infusion pressure and frequency. The permeability of coal increase significantly with the water infusion pressure improving under constant water infusion time and frequency. The permeability of coal increase significantly with the water infusion frequency improving under constant water infusion pressure and time. So the pulse water infusion time needs to ensure a better effect of preventing coal and gas outburst is gotten. Meanwhile the high pressure pulse water infusion pressure needs to improve under the existing technical conditions and not cause big coal fissure. The frequency of pulse water infusion needs to improve under the existing technical conditions. This research results have great theoretical value and practical significance on revealing the mechanism of coal seam pulse water infusion on permeability, enhancing the validity of the technological parameters design in coal seam water infusion and implementing the technology in the site.

Key words: Coal seam water infusion, pulse, liquid-solid coupling, permeability, stress

INTRODUCTION

Coal seam water infusion is a kind of effective measure for preventing coal and gas outburst and rock burst which can also reduce dust and coal dust explosion (He, 2006; Yu, 2005; Zhou and Lin, 1999). In the process of coal seam pulse water infusion, coal seam around the water infusion hole is loaded by the periodic change water pressure which caused a damage cumulative effect of the coal body around water infusion borehole, with increasing damage accumulation of coal, the permeability coefficient around coal drilling also changed. Seepage flow field and stress field was influenced by each other in the process of high pressure pulse water infusion. In the high stress state, without regard to change of the permeability coefficient will bring greater error, especially for high pressure pulse water infusion process, stress and seepage fields have strong coupling effects and the coal damage has increase during the water infusion process, the permeability coefficient of coal changed dynamically, so the coupling effects of stress field and seepage field must be considered in the process of coal seam high pressure pulse water infusion (Zhao, 1994; Mou *et al*., 2004; Louis, 1974).

There is a strong interaction liquid-solid coupling between the seepage field and stress field during coal seam pulse water infusion process. In this study, ABAQUS software is used to simulate the liquid-solid coupling laws during the coal seam pulse water infusion, during the coal seam pulse water infusion process, seepage field and stress field coupling analysis had important theoretical and practical significance for

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revealing increasing permeability mechanism and enhancing the effectiveness of water infusion technological parameters as well as field application.

NUMERICAL SIMULATION STUDIES

In the process of coal seam pulse water infusion, on the one hand, the coal seam around water infusion holes have different degrees damage is caused by permeate volume strength, on the other hand, the damage is caused by pulse water pressure which will cause a certain degree of accumulation damage effect (Zhu *et al*., 2013).

In the process of coal seam pulse water infusion, liquid-solid coupling effect exists in coal seam between the stress field and seepage field. Based on the basic principle of liquid-solid coupling, the dynamic liquid-solid coupling of stress and seepage field during coal seam high pressure pulse water infusion is simulated through secondary development of ABAQUS software, during this process the mathematical model of the strain accumulation model due to the periodic changes of pulse water pressure is embedded in SOIL module of ABAQUS software (Adachi *et al*., 2007; ABAQUS, 2009). The law of different parameters of high pressure pulse water infusion on the permeability of coal around infusion hole is gotten.

Dimensional simulation model: The dimensional simulation model with 1m cross section around water infusion hole is used in this study, the model length is 2 m, the width is 2 m and the diameter of water infusion hole is 0.075 m. Considering the problem as a plane strain problem, plane strain coupling unit (CPE4PH) is used as the unit type in ABAQUS. Numerical simulation model and the grid division are shown in Fig. 1.

Damage accumulation law of coal under cyclic loading: The plastic hysteretic loop of coal body around water infusion hole will appear in each infusion cycle during coal seam pulse water infusion. The hysteresis loop area in the early coal seam pulse water infusion displayed larger, with the increasing of pulse time, the hysteresis loop area produced by pulse water pressure will became smaller. The plastic strain will be generated by pulse water pressure, so the plastic strain change law reflected the damage evolution of coal body.

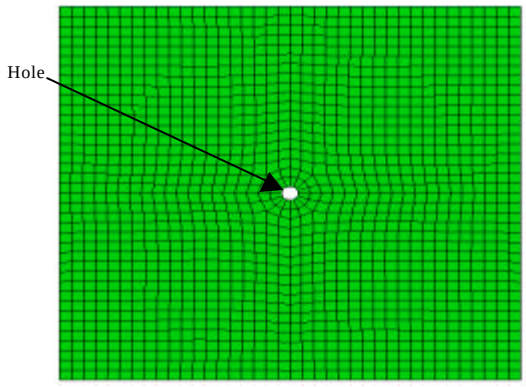

Fig. 1: Dimensional simulation model

The predecessors have done many researches about materials damage evolution under periodic load. According to the three stages damage evolution law of material, Xiao (2009) put forward axial strain accumulation inverted S model. This model can reflect the materials damage evolution law, the parameters are easily determined and engineering applications is convenient. Nonlinear axial strain damage accumulation model shown in Eq. 1 is used in this simulation:

$$\begin{cases} \varepsilon = \alpha\left(\dfrac{-\beta}{n/N-\beta}-1\right)^{1/p}\cdot\varepsilon' \\ \beta = 1+\left(\dfrac{1}{\alpha}\right)^{-p} \end{cases} \quad (1)$$

where, p is instability speed factor, the value range is [2,8]. α is the instability of the scaling factor, the value range is [0,1]. β is instability factor and β is nonlinear function of p and α. ϵ is axial strain, ε' is axial strain extreme of coal under periodic load.

Figure 2 is curve of ultimate strain-relative cycle at different α of Baodian mine coal sample cycle load experimental data by Yang (2006) when the p = 8, ε' = 1.1%. It can be seen from Fig. 2, the acceleration section proportion of curve ultimate strain-relative cycle is mainly influences by the parameter α. When α = 0.3, the acceleration section proportion of curve ultimate strain-relative cycle is smaller than α = 0.8 m. So, the greater the value of α, the acceleration section proportion is larger. According to the Baodian mine coal mine sample experimental data fitting, the suitable value of α is 0.5, it is the reference value in the process of this numerical simulation.

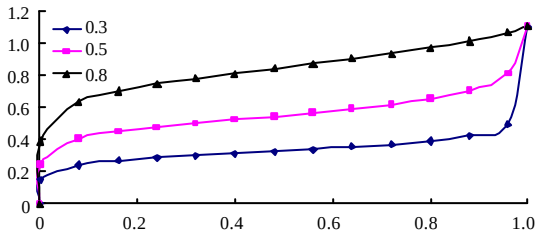

Fig. 2: Curve of ultimate strain-relative cycle at different p (α = 8)

Figure 3 is curve of ultimate strain-relative cycle at different p of Baodian mine coal sample cycle load experimental data by Yang (2006) when the α = 0.5, ε' = 1.1%. It can be seen from Fig. 3, the convergence rate of curve of ultimate strain-relative cycle is mainly influences by the parameter p. According to the Baodian mine coal sample experimental data fitting, the suitable value of p is 8, it is the reference value in the process of this numerical simulation.

Boundary conditions: The main parameters need to be set in numerical simulation process, the bulk density of coal γ = 14000 N m^{-3}, elastic modulus E = 1 GPa, Poisson's ratio v = 0.36, cohesive strength c = 2 MPa, friction angle ϕ = 25°. The upper and lower boundary of Fig. 1 is constrained, the entire boundary are set as constant pressure permeable boundary. The Mohr-Coulomb criterion is used as the coal yield condition. The seam pulse water infusion is simulated by SFLOW command and the pulse water pressure amplitude and frequency is defined by FLOW subroutine.

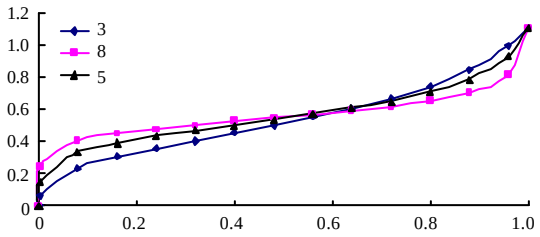

Fig. 3: Curve of ultimate strain-relative cycle at different p (α = 0.5)

Results and analysis

The impact of infusion time on coal permeability coefficient: The pulse water infusion frequency is 2 t min^{-1}, maximum water pressure is 9 MPa and the amplitude value is 3 MPa in this numerical simulation.

Figure 4 is dimensionless permeability coefficient distribution at different time around water infusion hole are respectively 1, 3, 5 and 10 min. It can be seen from it, with the increasing of water infusion time, the permeability coefficient around water infusion hole exhibited dynamically increased change law and continued to radiation spread around the infusion hole.

Figure 5 is curve of water infusion time-dimensionless permeability coefficient at two positions with 0.2 and 0.5 m at the bottom of water hole, it can be seen with the infusion time increases, permeability coefficient displayed nonlinear increasing

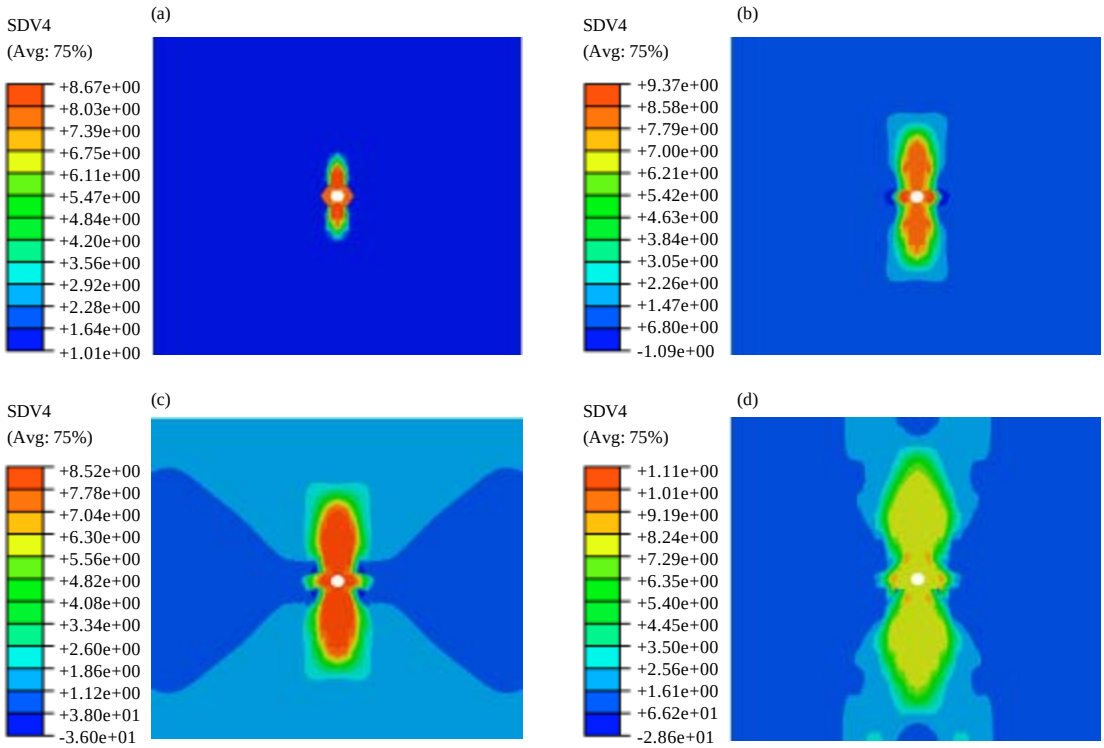

Fig. 4(a-d): Dimensionless permeability coefficient distribution at different time (a) 1 min, (b) 3 min, (c) 5 min and (d) 10 min

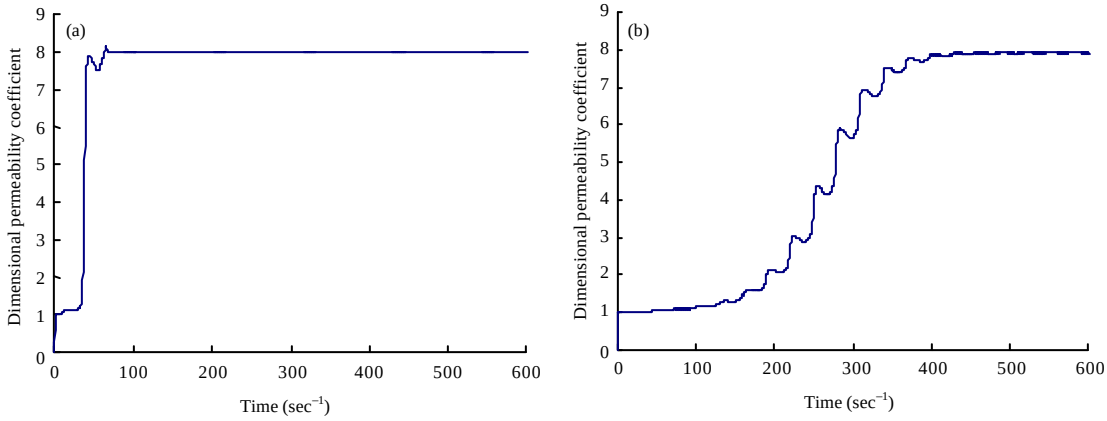

Fig. 5(a-b): Curve of time-dimensionless permeability coefficient (a) 0.2 m and (b) 0.5 m

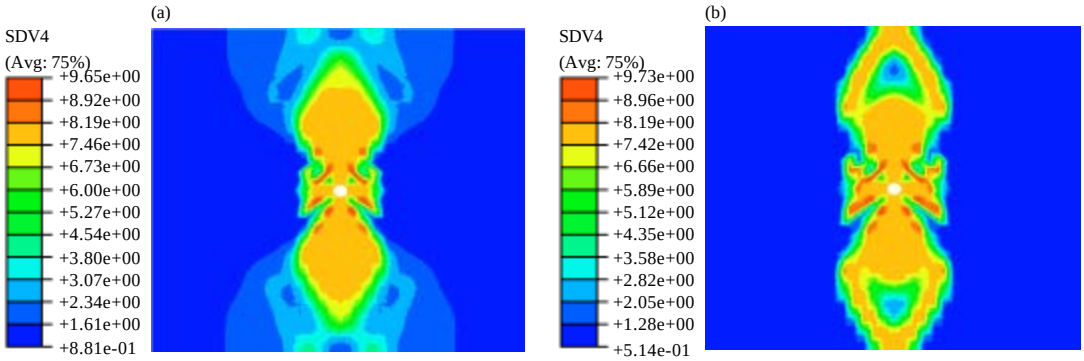

Fig. 6(a-b): Dimensionless permeability coefficient distribution at different pressure (15 min) (a) 10 MPa and (b) 12 MPa

trend, the reason is coal seam crack caused by pulse water pressure which continued to expand. The greater change in coal permeability coefficient, the larger water infusion impact radius can be gotten.

The impact of water pressure on coal permeability coefficient: The amplitude value is 3 MPa, pulse water infusion frequency is 2 t min^{-1} and the water infusion pressures are respectively 8, 10 and 12 MPa in this numerical simulation.

Figure 6 is the dimensionless permeability coefficient distributions at the water infusion pressure are 10 and 12 MPa at different pressure when pulse water infusion time is 15 min. It can be seen that the greater water infusion pressure, the greater permeability coefficient around the water infusion holes can be gotten. That is to say the higher water infusion pressure, it can effectively increase the influence range of coal seam water infusion, the better effect of pulse water infusion can be gotten.

Figure 7 is the curve of time-dimensionless permeability coefficient at different pressure when the water infusion pressures are respectively 8, 10 and12 MPa at the bottom of water hole 0.5 and 0.95 m. It can be seen that when other conditions constant, under different pulse water pressure, the coal permeability coefficient with time have uniform change rule. The permeability coefficient increases with the infusion time, the coal permeability coefficient in initial stage changes greatly. After a certain time of water infusion, permeability change rate become slowly. Lastly the coal permeability coefficient increases to a certain degree, the permeability coefficient increases rapidly, and it tends to stable. Overall, the evolution of coal seam permeability coefficient under high pressure pulse water infusion shows typical nonlinear three sections development law. The initial permeability change stage, the permeability coefficient constant change stage and accelerated damage stage, because of the change of coal seam permeability coefficient is mainly due to the damage of coal, so coal permeability coefficient change law are consistent with variation of three stage coal damage. The proportion of three stages is related with the coal seam water infusion

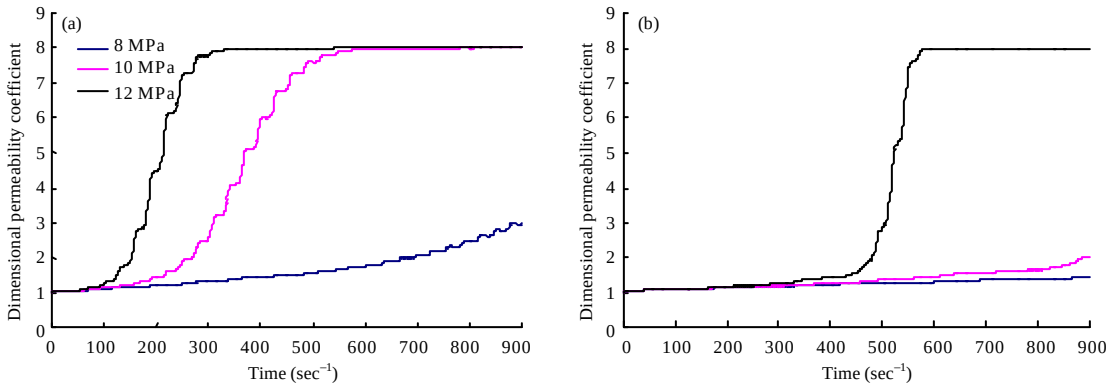

Fig. 7(a-b): Curve of time-dimensionless permeability coefficient at different pressure (a) 0.5 m and (b) 0.95 m

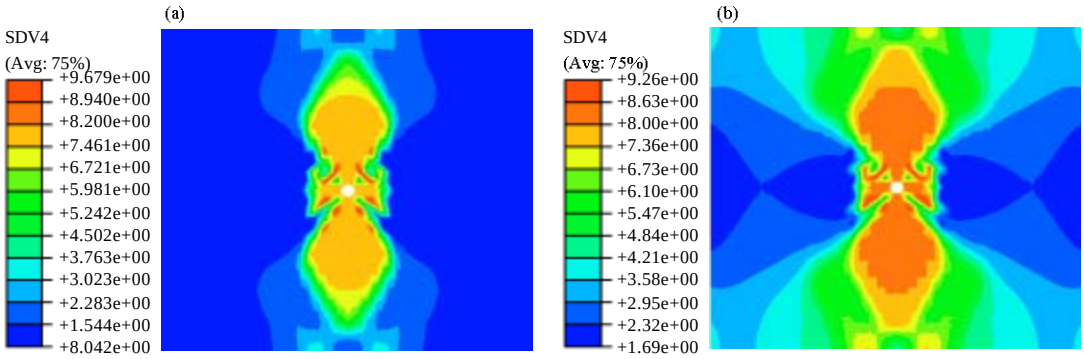

Fig. 8(a-b): Dimensionless permeability coefficient distribution at different frequency (15 min) (a) 1 t min^{-1} and (b) 6 t min^{-1}

parameters, physical and mechanical properties of the coal itself, as well as the stress state of coal. When coal seam infusion is in specific mine, physical and mechanical properties of coal body itself and the stress state is certain, then by changing the parameters of coal seam high pressure pulse water infusion can effectively improve the effect of coal seam water infusion efficiency.

It can be seen from Fig. 8 that, other conditions remain constant, on the same water infusion time, the higher water pressure; the greater coal permeability coefficient can be gotten. It shows water infusion pressure has significant effects on the permeability coefficient.

The results show that, the permeability of coal increase significantly with the water infusion pressure improving under constant water infusion time and frequency. So the pulse water infusion pressure needs to improve under the existing technical conditions and not cause big coal fissure in order to get a better effect of preventing coal and gas outburst.

The impact of pulse frequency on permeability coefficient: The pulse water infusion pressure amplitude value is 3 MPa, pulse water infusion pressure is 10 MPa, frequency are respectively 1, 2 and 6 t min^{-1}, the infusion pressure is 9 MPa in this numerical simulation. The influence of pulse frequency on permeability coefficient is analyzed.

Figure 8 is the dimensionless permeability coefficient distribution at different frequency when the infusion pressures frequency are respectively 1, 2 and 6 t min^{-1} when pulse water infusion time is 15 min. It can be seen that when other conditions constant, the bigger water pressures infusion frequency, the greater permeability coefficient around the water infusion holes can be gotten. That is to say the bigger infusion pressures frequency, it can effectively increase the influence range of coal seam water infusion and the better effect of pulse water infusion can be gotten.

Figure 9 is the curve of time-dimensionless permeability coefficient at different frequency when the

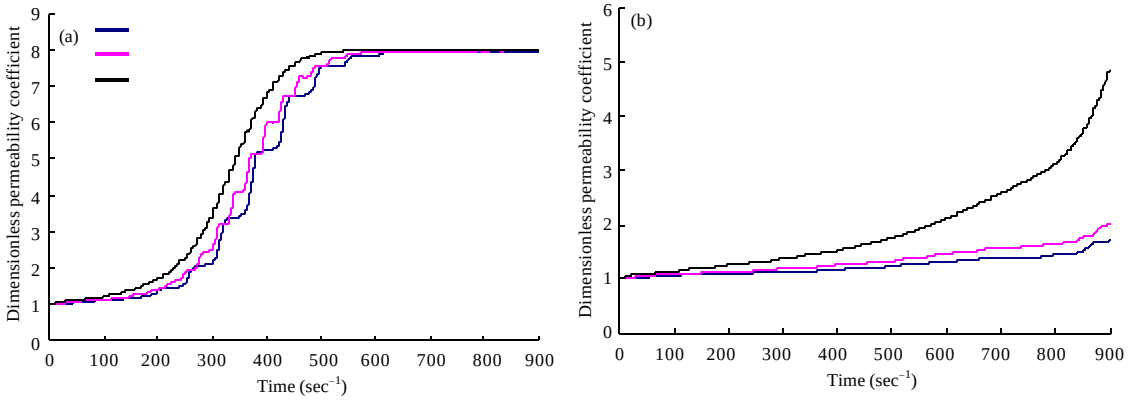

Fig. 9(a-b): Curve of time-dimensionless permeability coefficient at different frequency (a) 0.5 m and (b) 0.95 m

infusion frequencies are respectively 1, 2 and 6 t min^{-1} at the bottom of water hole 0.5 and 0.95 m. It can be seen that when other conditions constant, under different pulse water infusion frequency, the coal permeability coefficient change law with water infusion time have same change rule between Fig. 7 and 9. It can be seen from Fig. 9 that, other conditions remain constant, on the same water infusion time, the bigger water frequency; the greater coal permeability coefficient can be gotten. It shows infusion frequency has significant effects on the permeability coefficient. The frequency of high pressure pulse water infusion needs to improve under the existing technical conditions; in order to get a better effect of preventing coal and gas outburst is gotten.

CONCLUSION

Based on the basic principle of liquid-solid coupling, the dynamic liquid-solid coupling of stress and seepage field during coal seam high pressure pulse water infusion is simulated through secondary development of ABAQUS software, during this process the mathematical model of the strain accumulation model due to the periodic changes of pulse water pressure is embedded in SOIL module of ABAQUS software. The law of different parameters of high pressure pulse water infusion on the permeability of coal around the infusion hole is gotten:

- Numerical simulation results show that, during the process of coal seam high pressure pulse water infusion, the stress field and flow field are mutual influence and mutual restriction. The coupling of the field of stress and flow caused the physical and mechanical properties of coal in front of the working face changed, made the micro-fissure of the coal further expansion and transfixion, weakened the strength of coal, dynamic changed the coal skeleton softening, the permeability coefficient and damage of coal seam skeleton, these factors promote each other and preventing coal and gas outburst effectively
- The permeability coefficient of coal increase significantly with the water infusion time increasing under constant water infusion pressure and frequency. The permeability of coal increase significantly with the water infusion pressure improving under constant water infusion time and frequency. The permeability of coal increase significantly with the water infusion frequency improving under constant water infusion pressure and time. So, the high pressure pulse water infusion time needs to ensure a better effect of preventing coal and gas outburst. Meanwhile the high pressure pulse water infusion pressure needs to improve under the existing technical conditions and not cause big coal fissure. The frequency of high pressure pulse water infusion needs to improve under the existing technical conditions in order to get a better pulse water infusion effect

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