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Permeability enhancements of borehole outburst cavitation in outburst-prone coal seams

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ABSTRACT

Borehole outbursts eject coal power, create cavities and relieve in-situ stress while drilling cross-measure boreholes into outburst coal seams for pre-drainage. This paper highlights the borehole outburst cavitation to enhance the permeability of coal for the first time. Borehole outburst is a mechanical behavior, and the outburst trigger and development depend on the status of gas pressure gradient near the opening coal wall. It was testified that the high-pressure water, with 10–15 MPa in pressure and 20–30 m^3/h in flow, was feasible to remove the failure coal near the opening wall and stimulate a new set of outbursts, thus creating bigger cavities and better permeability enhancement. Furthermore, an outburst control system was designed for borehole outburst cavitation. The system contains an outburst stimulation subsystem, a gas drainage subsystem and a separation subsystem, thus ensuring the flow and the separation of outburst ejections within a relatively closed environment. The outburst cavity reconstitutes the in-situ stress and permeability of the surrounding coal mass, leading to a failure zone, a plastic zone and a visco-elastic zone. The failure zone and the plastic zone due to borehole outburst cavitation are both effective in permeability enhancement. Finally, a field test in the No. 10 coal seam at the Luling mine proved that the sufficient permeability enhancement scope is approximately twelve times of the cavity radius. The permeability enhancement promotes the increase of borehole distance from 5 m to 12 m, thus reducing 78.7% of boreholes in number for the pre-drainage of the No. 10 coal seam.

1. Introduction

Pre-drainage is one of the most important methods for gas control of outburst prone coal seams. In pre-drainage, surface “frac wells”, surface boreholes or underground boreholes are drilled directly into outburst prone coal seams and extract methane beyond the level strictly required to eliminate the outburst hazard in advance of mining.[1–6] Most of Chinese outburst prone coal seams have low permeability, which is three or four orders of magnitude lower than those of the US and Australia.[7–10] The low permeability, combining with complex geological conditions of outburst coal seams, causes the very low efficiency of surface pre-drainage, thus leading to the widespread underground borehole pre-drainage in China. Cross-measure boreholes or in-seam boreholes are generally drilled for pre-drainage, depending on the severity of outburst disasters of outburst-prone coal seams. Generally, medium- to high- outburst prone coal seams adopt cross-measure boreholes and low-outburst coal seams adopt in-seam boreholes for pre-drainage. To achieve the desired methane levels, enough to eliminate the outburst hazards, a large number of boreholes were drilled with a distance of 3–7 m for cross-measure boreholes and 2–5 m for in-seam boreholes.[11] In the future, pre-drainage will be harder due to the increasing depths of modern mines, which brings the increase of gas pressure and ground stress and the decrease of coal permeability. Some techniques must be taken to increase the coal permeability to reduce the heavy workload on borehole operation.

It is generally believed that reducing the in-situ stress is the only way of enhancing permeability of coal seams.[12] Besides of mining a protective seam, removal of coal mass directly from outburst coal seams is also an effective way of reducing the in-situ stress. Generally, three hydraulic methods, including dynamic cavity,[13–15] hydraulic flushing or injection[16–19,39] and hydraulic slotting[20–22] were greatly used to remove the coal mass from outburst coal seams. Dynamic cavity results in the stress-relaxed and stress-altered regions of exceptional permeability emanating from the cavity elliptically to intersect naturally occurring fractures and to effectively connect the formation cleat network to the wellbore. Hydraulic flushing creates some cavities in the coal seam, thus releasing the pre-existing stresses and generating extensive and intersection fractures upon creation of the opening. Hydraulic slotting

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cuts coal mass directly and forms macro-cracks and fractures in the coal seam. These cracks are connected with the drainage borehole and equivalent to enlarging the borehole length in coal seams. Generally, dynamic cavity is widely used on ground to increase the output of coalbed methane exploitation. Hydraulic flushing and hydraulic slotting are generally used to enhance coal permeability.

Outburst-prone coal seams contain huge internal energy of gas and strain energy of rock. A slight or violent disturbance, from borehole drilling to rock cross-cut coal uncovering, will trigger the release of energy, and then, coal and gas outbursts happen. Borehole outbursts eject gas into the operation site, thus leading to the gas explosion or flammable risk. As a result, borehole drilling had to be stopped and the drilling workers had to be evacuated from the working area. Borehole outbursts remove coal power and create cavities in the outburst coal seam, and these cavities are beneficial to permeability enhancement of coal seams like hydraulic flushing and hydraulic slotting.

This paper highlights the borehole outburst cavitation to eject coal mass, relieve in-situ stress and enhance the coal permeability for the first time. The aim of this paper is to investigate the mechanical behaviors, the stimulation methods and the permeability enhancement principle of borehole outburst cavitation; especially, the outburst stimulation and equipment are introduced. In the end, the effect of permeability enhancement of borehole outburst cavitation was field tested and verified.

2. Basic theory of borehole outburst cavitation

An outburst of coal and gas is the rapid release of a large quantity of gas in conjunction with the ejection of coal and possibly associated rock, into the working site in underground coal mines. Borehole outbursts happen in the cross-measure boreholes, and rock layers, between the outburst coal seam and the rock roadway, are the nature defense of resisting coal and gas outburst. Therefore, the energy release of borehole outbursts is relatively at small scale, and then, borehole outbursts are controllable and borehole outburst cavitation is feasible.

2.1. Mechanical process of borehole outbursts

The high-speed borehole drilling removes coal mass and uncovers the opening coal wall immediately, leading to the immediately stress transfer in the surrounding coal. The tangential stress and the vertical stress become concentrated, and the radial stress decreases ahead of the opening wall. Coal is a rather soft rock with low strength. The concentrated tangential stress and the concentrated vertical stress are generally big enough to destroy the coal mass near the opening wall, and then, the two concentrated stresses are transferred, thus forming the unloading stress area and the concentration stress area near the borehole,[23,24] as shown in Fig. 1.

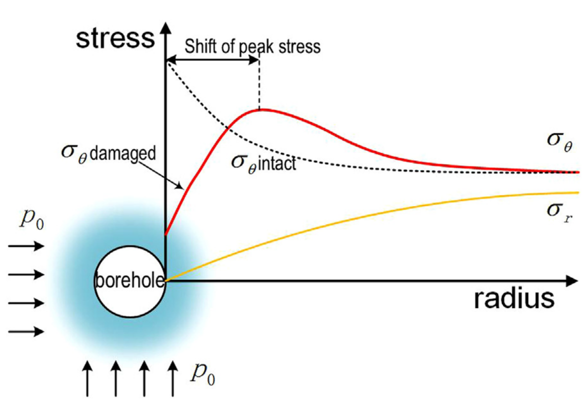

Fig. 1. Drilling-induced stresses around a borehole.

2.1.1. The trigger of borehole outbursts

In the unloading stress area, the tangential stress and the vertical stress are lower than the initial value. However, the radial stress further decreases and then reaches zero at the opening wall (Fig. 1). Meanwhile, the coal permeability rapidly increases as the plastic failure of coal occurs, which leads to the quick migration of gas. The gas pressure quickly rises from atmospheric pressure to the initial gas pressure. A high gas pressure gradient formed near the opening wall exerts a tensile effect on the coal,[40] as shown in Fig. 2(a).

The exposed coal, which has been extremely damaged by the induced tangential stress, undergoes a huge tensile stress near the opening wall. In this circumstance, the coal mass will be pulverized into tiny coal power because the high pressure free gas violently tears the damaged coal along the tips of the fractures and pores. Meanwhile, the high pressure gas dilates like a physical explosion and creates a gas storm on the wall, thus ejecting the tiny coal powder and triggering an outburst in the borehole.

2.1.2. The development of borehole outbursts

In the concentration stress area, the tangential stress and the vertical stress become concentrated, and the radial stress decreases (Fig. 1). This stress transfer leads to a decrease in the coal yield strength. When the concentrated stress exceeds the coal yield strength, the coal undergoes plastic failure. Coal is irreversibly damaged after plastic failure, and the internal fractures propagate to form good gas flow channels, thereby resulting in a rapid increase in the coal permeability.[41]

In borehole outburst, the ejection of coal power makes the immediate exposure of the new opening coal wall. Ground stress and gas pressure continue the above mentioned outburst process of destroying, pulverizing and ejecting coal near the new opening wall. This is the outburst development process.

2.1.3. The intermittency of borehole outbursts

In an ideal condition, the borehole outburst will develop continuously and create a bigger and bigger cavity in the coal seam.[25] However, it is impossible because of the restrained transit of outburst ejections. In borehole outbursts, the outburst ejections containing the ejected coal power, the ejected gas and the drilling water, transfer in a very narrow and long annulus which is approximately less than 30 mm wide and dozens of meters long. This annulus is a ring-shape space between the borehole wall and the drill pipe. As a result, the ejections are easy to be hindered or blocked during the transit process. When the annulus is hindered or blocked, the gas pressure and the radial stress in the borehole will increase gradually, thus leading to the decreasing of gas pressure gradient and tensile strength near the opening wall, as shown in Fig. 2(b). That means the internal energy of gas that is used to pulverize coal mass and eject coal power is reduced gradually. As a result, the borehole outburst is weakened gradually.

Unlike previous borehole drilling, the drilling pipe continues rotating in borehole outburst cavitation. If the pipe rotation disturbance loosens and clears out the hindered or blocked coal power, a high gas pressure gradient and a low radial stress come again, thus reconstituting a relatively huge tensile strength near the opening wall. As a result, the borehole outburst may be improved and developed. It can be seen that the outburst intensity changes frequently during borehole drilling, depending on the transit of outburst ejections. Otherwise, the gas pressure gradient decreases and the radial stress increases continuously, and the outburst intensity follows down until finally stops, as shown in Fig. 2(c).

Once borehole outburst stops, the seam gas in the surrounding coal mass desorbs and flows into the borehole space. The redistributions of fractures and permeability due to borehole drilling cause the gas pressure curve changed greatly, as shown in Fig. 2(d). The gas pressure curve has two break points. The gas pressure near the opening wall is approximately equal to the pressure in the borehole space because of