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Analysis on the multi-phase flow characterization in cross-measure borehole during coal hydraulic slotting

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ABSTRACT

Hydraulic slotting in a gas drainage borehole is an effective method of enhancing gas drainage performance. However, it frequently occurs that a large amount of slotting products (mainly the coal slurry and gas) intensely spurt out of the borehole during the slotting, which adversely affects the slotting efficiency. Despite extensive previous investigations on the mechanism and prevention-device design of the spurt during ordinary borehole drilling, a very few studies has focused on the spurt in the slotting process. The slotting spurt is mainly caused by two reasons: the coal and gas outburst in the borehole and the borehole deslagging blockage. This paper focuses on the second reason, and investigates the hydraulic deslagging flow patterns in the annular space between the drill pipe and borehole wall. Results show that there are six deslagging flow patterns when the drill pipe is still: pure slurry flow, pure gas flow, bubble flow, intermittent flow, layering flow and annular flow. When the drill pipe rotates, each of those six flow patterns changes due to the Taylor vortex effect. Outcomes of this study could help to better understand the slotting-spurt mechanism and provide guidance on the anti-spurt strategies through eliminating the borehole deslagging blockage.

1. Introduction

Borehole gas drainage should normally be conducted prior to mining the coal with high gas content and low permeability, to prevent gas-related incidents (e.g. coal and gas outburst, gas accumulation and gas explosion) and decrease the ventilation costs [1–6]. Based on its position, there are mainly two types of boreholes: in-seam borehole and cross-measure borehole [7]. Because of its high safety degree, the cross-measure borehole drainage is widely adopted in many coal mines. As shown in Fig. 1, the cross-measure borehole is drilled from a roadway excavated in rock near the targeted coal seam, thus the rock layer between the roadway and the coal seam plays a role of protection for the borehole drilling work. However, the borehole drainage performance is not good in some countries where the occurrence condition of coal mine methane is complicated, mainly reflecting in high gas content and low permeability [8–10]. For instance in China, the coal permeability coefficient is approximately four orders of magnitude smaller than that permeability value in the US where the gas drainage technique is relatively mature [11,12]. Therefore, some extra measures should be taken in the borehole to increase the permeability value and enhance the drainage performance. Those measures include the hydraulic slotting, hydraulic fracturing and loosening blasting, among which, the hydraulic slotting is an effective one and applied in many coal mines [11,13–17]. In this measure, the slots are created in the coal seam using the high-pressure water jet (Fig. 1). Those slots could help to relieve the stress and increase the coal permeability, thus increasing the drainage area and drainage efficiency of a single borehole.

However, when the hydraulic slotting is conducted in the coal seam with high gas content, low permeability and high in-situ stress, the coal and gas outburst in the borehole is very likely to happen. This results in a large amount of slotting products (mainly the coal slurry and gas) intensely spurt out from the borehole during the slotting process (Fig. 2), which could damage the drilling rig and cause gas accumulation near the drilling site, and even block the roadway and halt the borehole slotting process in some severe cases [19,20]. In fact, the spurt phenomenon also frequently occurs in the process of ordinary borehole drilling, and a large number of studies have been conducted on it. Liang studied the stress changes around borehole in the drilling process, and explained the stacking damage related to stress variation and concluded that the borehole spurt is more likely to occur in the coal area with post-peak stress,

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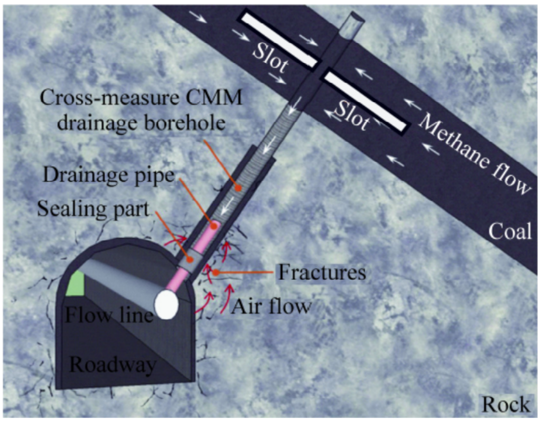

Fig. 1. Schematic diagram of the cross-measure borehole methane drainage with hydraulic slots (modified from Liu et al. [18]).

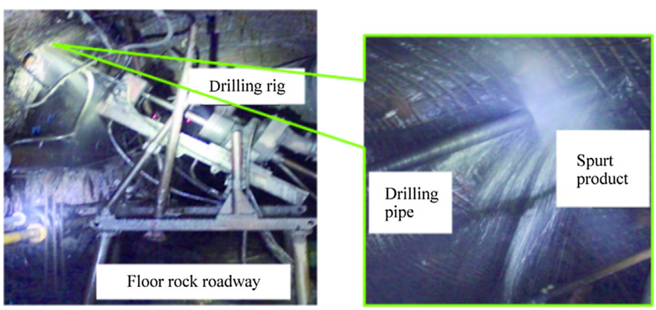

Fig. 2. Picture of the spurt during hydraulic slotting.

finally, the initiation and development of the spurt are given from perspective of the mechanical field changes [21]. Yao et al. theoretically established the borehole-drilling spurt model for outburst-threat coal seam. Meanwhile, they obtained the analytic solutions of the spurt speed and amount, which could provide the anti-spurt device design with quantitative guidance [22]. Wang et al. analyzed the spurt mechanism during borehole drilling with respect to the coal deformation and instability [23]. To control the spurt during the cross-measure borehole drilling, Jing and Tang designed an anti-spurt device, which could prevent gas accumulation and guarantee the drilling safety and efficiency [24]. To cope with the issues of water, gas and coal chips in the coal-prospecting borehole, Li developed a multipurpose underground borehole-blowout preventer, and showed good blowout-control performance during borehole drilling [25]. Li et al. designed an anti-spurt device which is composed of borehole sealing section, the connection parts and the gas-water separator, and drains the spurt gas into the drainage main pipe and collect the coal slurry into the device [26]. Zhu et al. improved the traditional anti-spurt device by adding the spurt-blocking part, to control the extremely intense spurt [27]. In summary, previous studies mainly concentrated on the mechanism and prevention-device design of the spurt in ordinary borehole-drilling process. In contrast, few studies has been conducted to investigate the spurt phenomenon during hydraulic slotting.

It should be noted that as high-pressure water jet is adopted in the slotting process, there are many new characteristics for the hydraulic-slotting spurt compared with the borehole-drilling spurt, and the former is normally more intense. Therefore, the spurt phenomenon in the hydraulic-slotting process will be the objective of this study. This spurt is mainly induced by two issues: the coal and gas outburst around borehole and the borehole deslagging blockage (the deslagging represents that the slotting products including coal slurry and gas getting out of the borehole), the spurt always occurs when the deslagging-blocked borehole reopens. As the coal and gas outburst has been put forward and extensively investigated for many years, this study focuses on the borehole deslagging blockage during slotting. The hydraulic deslagging flow patterns in the annular space between the drill pipe and borehole wall will be analysed, as well as some flow patterns' characteristics. Research outcomes could help to better understand the mechanism of slotting spurt and provide guidance for prevention strategies, guaranteeing the safe and effective hydraulic slotting.

2. Deslagging flow during hydraulic slotting

During the hydraulic slotting, the slotting products (mainly the coal slurry and gas) are continuously discharged through the annular space between the drill pipe and borehole wall as shown in Fig. 3. In this inclined deslagging channel, the deslagging power mainly includes the gravity of slotting products, the continuously increasing expansion force of gas and the water-jet pressure. The mechanical criteria for slotting deslagging is

$$mg\sin\beta + F_g + F_w \geqslant F_f \tag{1}$$

where m is the mass of the slotting products, including the coal slurry, gas and small coal or rock; g the gravitational acceleration, which is about 9.8 m/s^2; β the inclination angle of the borehole, which normally ranges from 30° to 60° in the coal mine; F_g and F_w the expansion forces caused by the gas and the water-jet pressure, respectively; and F_f the frictional resistance in the deslagging channel.

When Eq. (1) satisfies, the spurt products would be accelerated along the deslagging channel. Meanwhile, that channel is very less prone to experience blockage. On the contrary, if Eq. (1) does not satisfy, the deslagging rate will continuously reduce due to the adverse effect of frictional resistance, in which case, borehole blockage is very likely to occur. As a result, both the probability and intensity of spurt increase.

The flow rate in this deslagging path could be expressed as

$$v = \frac{4Q}{\pi(D^2 - d^2)} \tag{2}$$

where Q is the volume flow rate in the annular space, which mainly consists of the coal slurry and gas; D the diameter of borehole; and d the diameter of the drill pipe.

In coal mines, the borehole diameter (D) is commonly 90–110 mm, and the drill-pipe diameter (d) is around 50 mm. The water-

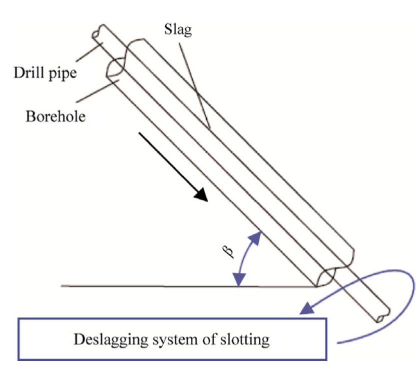

Fig. 3. Schematic diagram of the hydraulic-slotting deslagging system.

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