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A new design of foam spray nozzle used for precise dust control in underground coal mines

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ABSTRACT

In order to improve the utilization rate of foam, an arc jet nozzle was designed for precise dust control. Through theoretical analysis, the different demands of foam were compared amongst arc jets, flat jets and full cone jets when the dust source was covered identically by foam. It is proved that foam consumption was least when an arc jet was used. Foam production capability of an arc jet nozzle under different conditions was investigated through experiments. The results show that with the gas liquid ratio (GLR) increasing, the spray state of an arc jet nozzle presents successively water jet, foam jet and mist. Under a reasonable working condition range of foam production and a fixed GLR, foam production quantity increases at first, and then decreases with the increase of liquid supply quantity. When the inner diameter of the nozzle is 14 mm, the best GLR is 30 and the optimum liquid supply quantity is 0.375 m^3/h. The results of field experiments show that the total dust and respirable dust suppression efficiency of arc jet nozzles is 85.8% and 82.6% respectively, which are 1.39 and 1.37 times higher than the full cone nozzles and 1.20 and 1.19 times higher than the flat nozzles.

1. Introduction

Dust is one of the main causes of hazards in the mining process in coal mines. It can lead to coal dust explosions and coal workers' pneumoconiosis (CWP), and cause huge casualties and property losses. At present, coal dust explosions have been effectively controlled, but the number of pneumoconiosis deaths is far more than the total sum of deaths caused by mine fires, gas explosions and other mine accidents. For example, in China, the number of deaths caused by mine accidents was less than 1500 in 2012, but the people who died due to pneumoconiosis are more than 1800. Now, water sprays are widely used for dust prevention and suppression in the mining process in coal mines, but dust suppression efficiency is too low to meet with the actual demand [1–3]. Foam has an excellent effect on dust control with the mechanism of wetting, adhesion, interception, and settlement, etc. It is a type of dust control technology with significant research value and good prospects for application [4]. In recent years, practical applications and research on dust suppression by foam have been gradually increased in coal mines [5–7]. Field practice and research shows that dust suppression with foam faces an urgent problem: the cost is much higher, but foam utilization rate is low. In order to solve this problem, it is imperative to develop precise dust control technology. Through the precise use of foam spraying, the utilization rate of foam is increased, which decreases the cost.

In research on precise dust control with foam, the spray pattern of the foam nozzle is an important research objective because it has a direct effect on the utilization rate of foam. The two conventional foam jets are 'flat' and 'full cone'. Wang et al. designed a full cone nozzle and applied it to control dust at a heading face in the Xuehu Coal Mine in China [8]. The flat jet nozzle is widely used to control dust and harmful emissions. For instance, Singh M M and Laurito A W adopted a flat jet nozzle in their experiments on dust control with foam at a working face in a mine in Utah in the United States [9]. Ren designed a flat jet nozzle with a V-groove and carried out field applications at a heading face in the Xin'an Coal Mine in China [10]. Song designed two kinds of flat jets; one of them is shaped like a duck bill whilst the other is a flat jet composed of several full cone jets [11]. Another kind of foam nozzle-an 'arc jet' nozzle-was designed by Wang et al. Its stream cross section resembles an arc-shaped belt and, at present, the arc jet nozzle is being used in several coal mines in China.

Firstly, through theoretical analysis, this paper will show that the arc jet is the best choice for achieving precise foam dedusting. Secondly, through experiment, the foam production

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capability is studied to confirm the best operating conditions for foam production. Finally, the results of field tests of the new foam nozzle will be presented.

2. Advantages of arc jets

2.1. Framework of arc jet nozzle

The newly-designed arc jet nozzle incorporates a main body combined with a diversion object. The diversion object is a semi-cone and the main body of the nozzle contains an inlet, outlet and an extended segment, as shown in Fig. 1. The extended segment controls the pattern of the arc jet, together with the diversion object, which can turn the foam into an arc jet.

The foam jet produced by the arc jet nozzle is as shown in Fig. 2.

2.2. Comparison between arc jet and other spray patterns

Chinese mechanized mining equipment is comprised mainly of shearers and roadheaders, of which more than 90% of the cutting head (or drum) is in vertical-axis rotation, and therefore the source of dust presents an annular pattern, as showed in Fig. 3.

Taking a vertical-axis roadheader as an example, three kinds of foam jet shapes can be analyzed: the full cone jet; the flat jet and the arc jet. Prior to making a comparison, the following assumptions can be made: nozzles are arranged equally in the same cycle at the root of the cutting arm; the number of nozzles is n, when $n < 3$; the three kinds of nozzles cannot all enclose the dust source. Therefore, according to objective reality, the number of nozzles should be a positive integer greater than 2. Suppose that the minimum thickness of foam that can effectively prevent the escape of dust is d_{min}, the largest circle diameter of the cutting head is d_c, and the jet speed of foam is v. When using a full cone jet, flat jet or arc jet, the minimum total volume of the foam consumption is, respectively, V_{cone}, V_{flat}, V_{arc} and the minimum total areas of their impact sections are S_{cone}, S_{flat} and S_{arc}.

(1) When using a full cone jet, the length of the strings confirmed by any two overlapping adjacent impact sections is the shortest path for the dust particles to exit the surroundings. The length of the string from point 'a' to point 'b' (which is shown in Fig. 4a) is d_{min}, taking the points 'a' and 'b' as points on a circle and making concentric circles for the largest circle of the cutting head. If L is the distance between the inner concentric circle and the largest circle of the cutting head, it can be seen from Fig. 4a that overlapping regions are formed by any two adjacent full cone impact sections. Therefore, the minimum value of the total impact section that is produced by the full cone jets can be seen as being comprised of a ring-shaped region S_{torus}, n overlapping regions $S_{overlap}$ and $2n$ remaining regions S_{remain}. Then,

$$V_{cone} = vS_{cone} = v(S_{torus} + nS_{overlap} + 2nS_{remain}) \quad (1)$$

(2) When using a flat jet, the impact section of a single flat jet is a belt-shaped region. The two adjacent flat jets should overlap, and the width of the impact section L_b should be d_{min}, as shown in Fig. 4b. The shortest path that the dust particles take through the impact section would appear at the overlapping region. Therefore, the length of the shortest escape path is d_{min}. Calculating the belt length L_a performed through the geometrical relationships, the minimum volume that is needed when using flat jets is:

$$V_{flat} = vS_{flat} = vnL_aL_b = nvd_{min}\left(2d_{min}\sin\frac{180}{n} + d_c\tan\frac{180}{n}\right) \quad (2)$$

(3) When using an arc jet, no matter how many nozzles are used, the total impact sections formed around the cutting head should be as shown in Fig. 4c. It is worth noting that two adjacent arc jets can theoretically have a seamless connection without overlapping. Then, the minimum volume that is needed by arc jets is:

$$V_{arc} = vS_{arc} = v\left[\pi\left(\frac{1}{2}d_c + d_{min}\right)^2 - \pi\left(\frac{1}{2}d_c\right)^2\right] = \pi vd_{min}(d_{min} + d_c) \quad (3)$$

(4) Comparisons: In order to compare V_{cone} and V_{arc}, half of the foam that goes through the overlapping regions and $2n$ crescent regions can be ignored. Introducing the fictitious minimum foam volume V^*_{cone} when using full cone nozzles, we have:

Fig. 1. Arc jet nozzle.

Fig. 2. Jet shape of arc jet nozzle.

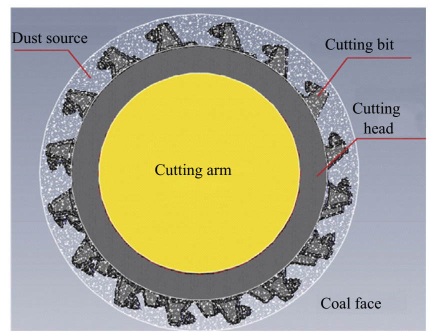

Fig. 3. Schematic diagram of a dust source.