



基于塑性区体积的掘进机截割减尘方法及综合降尘技术研究

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基于塑性区体积的掘进机截割减尘方法及 综合降尘技术研究

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摘要:掘进机快速掘进巷道为煤矿高效生产提供了有力支撑,但高强度截割也会产生大量粉尘。为减少掘进机截割产尘量,降低掘进面浮尘浓度,提出通过改变掘进机截割参数实现源头减尘的方法。该方法从镐型截齿侵入煤体产生粉尘的5个步骤出发,考虑塑性区体积大小与镐型截齿齿尖角度之间的关系,减小截齿齿尖角度和截割头旋转速度以降低粉尘产生量,在煤矿综掘面开展了现场减尘试验,分析不同截割参数下产尘量的变化。为进一步治理掘进面粉尘,在减尘基础上设计了以掘进机自带外喷雾和湿式除尘风机为主、控尘风幕和感应式全断面水幕帘为辅的综合降尘方案。在掘进机司机、掘进机机身后5 m和全断面水幕帘后方2 m处设定测尘点考察降尘效果。结果表明,当更换齿尖锥角更小的截齿后(92° & 54 rpm),掘进机司机处呼尘和全尘平均质量浓度与原始条件相比分别降低了18.5%和9.1%;再降低截割头转速后(92° & 27 rpm),呼尘和全尘平均质量浓度与原始条件相比降幅为34.5%和15.8%。配套采取综合降尘措施后,掘进机司机处呼尘平均质量浓度降至4 mg/m³,降尘率为90.6%,全尘平均质量浓度降至20.5 mg/m³,降尘率为93.6%;掘进机机身后5 m处的回风侧呼尘和全尘平均质量浓度分别降至6.6 mg/m³和30.1 mg/m³,降尘率分别为86.9%和91.5%,水幕帘后方2 m处呼尘和全尘平均质量浓度分别降至2.4 mg/m³和3.9 mg/m³,降尘率分别为91.3%和95.1%。

关键词:掘进机;粉尘;截割减尘;塑性区体积;截割参数;综合降尘

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Dust reduction method based on the volume of plastic zone and a comprehensive control technology for roadheader cutting

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Abstract: Roadheaders play a vital role in enhancing coal mine production efficiency, but they also generate a significant amount of dust during high-intensity cutting. To address this issue and make dust control more manageable, an approach was developed by adjusting the cutting parameters of the roadheader. This approach is based on analyzing the five stages of dust generation during pick penetrating into the coal, while systematically considering the relationship between the plastic zone volume and the tip angle of the pick. By reducing the angle of the cutting tooth tip and the rotation speed of the cutting head, the amount of dust generated would be decreased. Field experiments were carried out at a tunneling working face to investigate the variations in dust production under different cutting parameters. To

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control dust at the tunneling working face, a comprehensive dust control method was implemented, including external water spray, a wet dedusting fan, an air curtain, and an inductive full-section water curtain. Dust measurement points were established at the driver of the roadheader, 5 meters behind the roadheader, and 2 meters behind the full-section water curtain to assess the effectiveness of dust control at different locations. The results revealed that replacing the conical picks with a smaller tip angle (92° & 54 rpm) resulted in decrease of average mass concentrations of respirable dust (MRD) and total dust (MTD) with 18.5% and 9.1% lower than the original conditions. Additionally, reducing the cutting head speed (92° & 27 rpm) led to MRD and MTD reductions of 34.5% and 15.8% compared with the original conditions. After implementing comprehensive dust control measures, substantial reductions in MRD and MTD were observed at different locations. At the driver of the roadheader, the average MRD was reduced to 4 mg/m^3 , with a dust reduction rate of 90.6%. And the average MTD decreased to 20.5 mg/m^3 , with a dust reduction rate of 93.6%. At 5 meters behind the roadheader, the average MRD and MTD were reduced to 6.6 mg/m^3 and 30.1 mg/m^3 , with dust reduction rates of 86.9% and 91.5%, respectively. At 2 meters behind the water curtain, the average MRD and MTD were reduced to 2.4 mg/m^3 and 3.9 mg/m^3 , with dust reduction rates of 91.3% and 95.1%, respectively. These findings demonstrate the effectiveness of the proposed method in significantly reducing dust generation and ensuring a safer working environment.

Key words: roadheader; dust; dust reduction during heading; volume of plastic zone; cutting parameters; comprehensive dust control

0 引言

粉尘是煤矿的主要灾害之一,在掘进、采煤、洗选等过程中都会产生^[1-4]。因长期吸入大量粉尘导致的尘肺病几乎无法治愈,是我国第一大职业病^[5-7]。我国累计报告尘肺病例超过 90 万人,绝大部分患者来自煤矿企业^[8-9];2022 年全国职业病新增 11 108 例,其中职业性尘肺病 7 577 例占 68%,因尘肺病死亡 9 613 例^[10]。高浓度煤尘悬浮在空气中还可能导致煤尘爆炸或瓦斯煤尘爆炸事故,是煤矿危害最严重的事故之一^[11-13]。

采用掘进机高强度截割作业,某些煤矿综掘面未采用降尘措施时的原始粉尘质量浓度可达 $1\,500 \text{ mg/m}^3$ ^[14],对工作人员的身心健康和企业安全生产有严重威胁。综掘面的粉尘防治技术发展迅速,如喷雾降尘^[15]、除尘器^[16-17]、风幕控尘^[18]等,这些技术的应用显著降低了综掘面粉尘浓度,但当前制定降尘方案时,在减少粉尘产生量方面的考虑仍有不足。粉尘本质上是体积较大的煤体受截齿截割破碎后产生的细微颗粒,因此截割参数是影响粉尘产生的重要外在因素。有学者开展试验后发现,当截割深度较小时,产生的碎块尺寸较小,截齿间距离较大时产生的碎块尺寸也随之增大^[19-20]。但这些研究中收集的碎块尺寸通常超出了粉尘的粒径范围(小于 $75 \mu\text{m}$),其研究重点在于高效截割而非粉尘产生。

鉴于此,笔者通过分析掘进机镐型截齿侵入煤体产生的塑性区体积,提出优化截割参数实现减少粉尘产生的方法,在神东煤炭集团下属某矿综掘面进行现场减尘试验,测定粉尘浓度变化以评价减尘效果,在此基础上设计了以掘进机外喷雾、湿式除尘风机、风幕控尘和全断面水幕帘隔尘相结合的综合

降尘技术治理综掘面减尘后的剩余粉尘,在掘进机司机位置、掘进机机身后方以及水幕帘后方分别设定测尘点,实测结果表明降尘效果显著。研究成果可为煤矿综掘面减尘降尘措施的制定提供借鉴和参考。

1 基于塑性区体积的减尘方法

通过分析截齿截割煤体的过程,将截齿侵入煤体直至破裂产生粉尘分为 5 个步骤,即压碎区形成、粉化核形成、裂纹萌生及扩展、自由面形成和粉化核约束解除。在粉化核外围还有发生塑性变形的塑性区,该区域内同样会产生粉尘,其所受作用力来自于粉化核的传递,破坏程度较小,产生的粉尘粒径通常大于粉化核内的粉尘粒径。塑性区和粉化核是截齿侵入煤体时产生粉尘的主要区域,该区域体积越大,产生的粉尘量越多,定量计算出该区域体积可评价产尘量的多少。塑性区体积大小基于“钝截齿”侵入煤体的空腔扩展模型计算,该模型中认为煤体塑性区的产生服从摩尔-库伦准则,截齿侵入速度远小于煤体内裂纹扩展速度,其侵入过程可认为是准静态加载。如图 1 所示,伴随截齿持续进入煤体,塑性区体积逐渐增加,当这一区域所受截割力超过煤体的强度极限时发生破碎。塑性区半径由式(1)计算^[21],可以看出,半径的增减仅和截齿齿尖锥角正相关,侵入煤体的截齿锥角越大,在煤体产生的塑性破碎区体积也越大。笔者通过实验室试验验证了这一关系^[22],采用不同齿尖锥角的截齿侵入煤体,收集产生的粉尘并测定浓度和粒径分布,发现利用齿尖锥角越大的截齿截割,塑性区越大产生的粉尘量越多,如图 2 所示。基于此,提出通过减小掘进机截齿齿尖角度达到减少掘进机截割产生量的方法。

$$r_* = \xi_* d C / \left[(1 + \mu) \xi_*^{\frac{K_d+2}{K_d}} - \mu \xi_*^{\frac{2K_p-2}{K_p}} \right] \quad (1)$$

式中: r_* 为塑性区半径, m; ξ_* 为塑性区半径与截齿齿尖和煤体的接触半径之比; d 为截齿侵入深度, m; K_d 为膨胀因子, $K_d = (1 + \sin \psi) / (1 - \sin \psi)$, ψ ($\phi \geq \psi \geq 0$) 是剪胀角, ($^\circ$); K_p 为被动系数, $K_p = (1 + \sin \phi) / (1 - \sin \phi)$; ϕ 为内摩擦角, ($^\circ$); $C = [G(K_p + 2) / 3\sigma_c]$, 其中 G 为剪切模量, MPa, σ_c 为单轴抗压强度, MPa; μ 为与煤体膨胀因子、被动系数以及泊松比有关的常数。

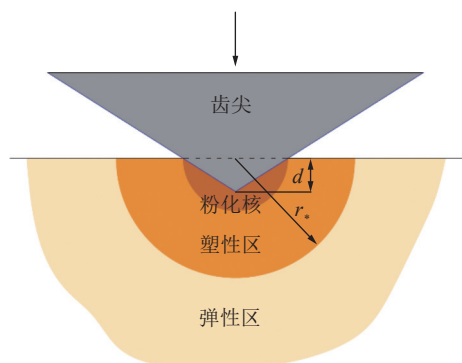


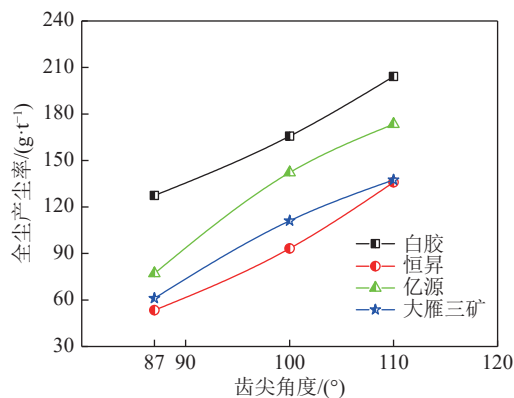
图 1 粉化核及塑性区示意

Fig.1 Schematic diagram of pulverized core and plastic zone

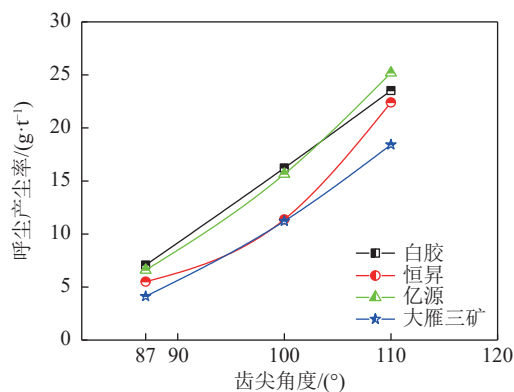
2 掘进机截割减尘方法试验

根据上述分析结果可知,减小掘进机镐型截齿齿尖角度可以显著降低粉尘产生量。为评价在掘进面现场实际应用中的减尘效果,在神东煤炭集团下属某现代化矿井开展现场试验。该煤矿位于内蒙古自治区鄂尔多斯市伊金霍洛旗境内,井田面积 13.62 km²,地质储量 2.12 亿 t,年生产能力 300 万 t/a。本研究在主斜井延伸巷开展,该巷道为全煤巷道,断面宽 5.6 m、高 3.5 m,综掘面瓦斯绝对涌出量 0.14 m³/min,所需风量为 340 m³/min。采用的 EBZ260H 型掘进机机身总长 11.9 m,截割头最大外径 1 186 mm、长 1 068 mm,自转速率为 54/27 rpm,工作转速为 54 rpm,装有 45 个齿尖锥角为 110 $^\circ$ 的镐形截齿。为了减少粉尘产生量,降低呼尘占比,采用该矿备用截齿(齿尖锥角为 92 $^\circ$)整体替换原有截齿(图 3),两种截齿均为掘进机截割头专用镐型截齿,除齿尖大小不同外其他位置的差异对粉尘产生影响很小。掘进机截割头转速较高时也可能造成粉尘产生浓度的增加,因此将截割头转速从 54 rpm 降低至 27 rpm,以进一步探究截割速度对产尘量的影响。

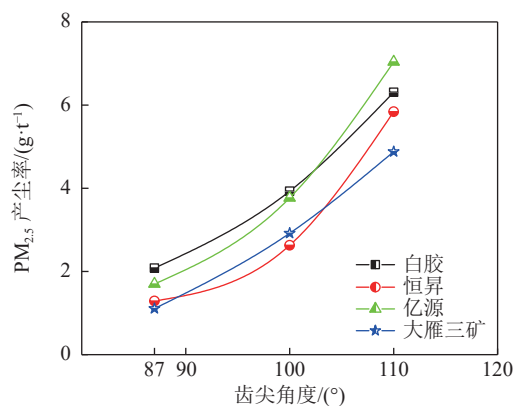
参照 AQ1020—2006《煤矿井下粉尘综合防治技术规范》和 GBZ/T192.1—2007《工作场所空气中中粉



(a) 全尘



(b) 呼尘

(c) PM_{2.5}图 2 截齿齿尖角度和产生率的关系^[22]Fig.2 Relationship between tip angles of conical pick and rate of dust generation^[22]

尘测定》中关于作业场所粉尘浓度测定的规定,将测尘点设置在掘进机司机处。利用两台 AKFC-92A 粉尘采样器(图 4)分别采取呼尘和全尘,采样流量为 20 L/min,采样时间为 15 min,高度为人体呼吸带所在高度。当不开启除尘设备时全尘浓度可能较高,因此采用直径为 75 mm 的滤膜,滤膜使用前后称量时均经过干燥、除静电处理。根据截齿齿尖锥角和截割头转速的不同,将截割条件划分为原始截割(110 $^\circ$ & 54 rpm)、更换截齿(92 $^\circ$ & 54 rpm)以及降低

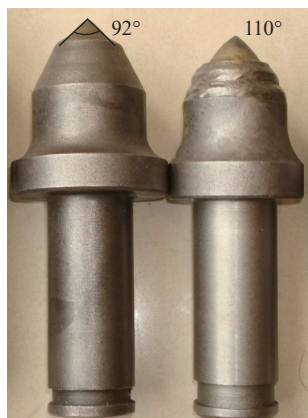


图3 齿尖锥角分别为 92°和 110°的截齿

Fig.3 Conical picks with the tip angles of 92° and 110°



图4 AKFC-92A 粉尘采样器

Fig.4 Dust sampling machine (AKFC-92A)

转速(92° & 27 rpm)共 3 种条件, 每种条件下全尘和呼尘均测定 3 次取平均值。

图 5 给出了不同截割条件下掘进机司机处的呼尘和全尘平均浓度。在原始截割条件下(110° & 54 rpm), 产生的呼尘和全尘平均质量浓度分别为

64.6 mg/m³ 和 381.5 mg/m³, 当更换齿尖锥角更小的截齿后(92° & 54 rpm), 呼尘和全尘质量浓度降低至 52.5 mg/m³ 和 346.8 mg/m³, 与原始条件相比分别降低了 18.5% 和 9.1%; 再降低截割头转速后(92° & 27 rpm), 产生的呼尘和全尘平均质量浓度分别为 42.2 mg/m³ 和 321.3 mg/m³, 与原始条件相比降幅分别达到了 34.5% 和 15.8%。

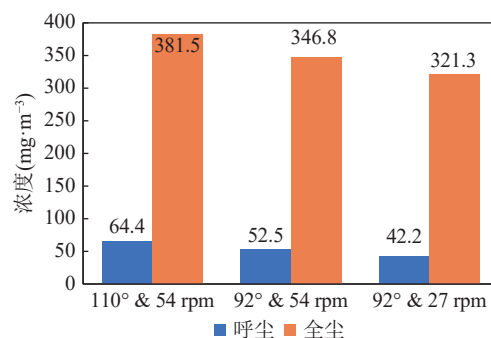
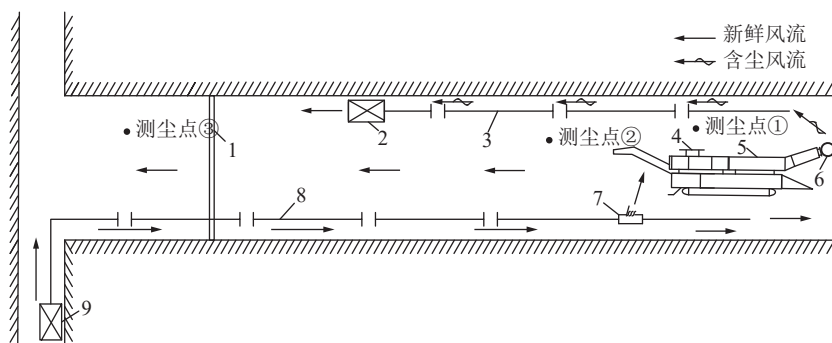


图5 不同截割条件下的粉尘质量浓度

Fig.5 Concentration of dust under various cutting conditions

3 综掘面高效综合降尘

综掘面现场实测结果表明, 改变掘进机截齿齿尖角度和截割头旋转速度后, 显著减少了粉尘产生量, 降低了粉尘治理难度。在此基础上, 针对掘进机截割头旋转截割、掘进机星轮和掘进机刮板运输转载点等主要产尘部位, 设计了以掘进机自带外喷雾和湿式除尘风机为主、以自启闭式控尘风幕和水幕帘为辅的综合降尘方案, 各降除尘设备布置如图 6 所示。



1—感应式全断面水幕帘; 2—湿式除尘风机; 3—钢圈风筒; 4—司机处; 5—掘进机; 6—截割头; 7—控尘风幕旋流器; 8—柔性风筒; 9—局部通风机

图6 综合降尘技术布置示意

Fig.6 Arrangement of comprehensive dust reduction technologies

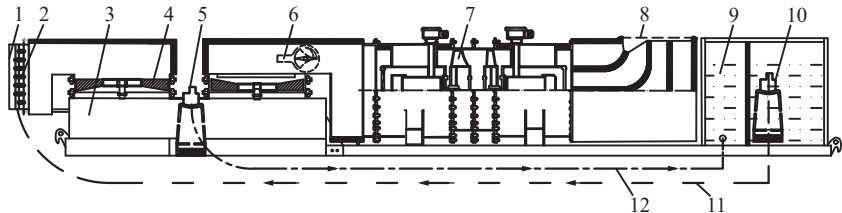
3.1 湿式除尘风机抽尘

综掘面通风方式为长压短抽式通风, 抽出式风机为 KCS-500DZ 型矿用湿式除尘风机, 如图 7 所示。

该风机由吸风口、雾化系统、积水盒、旋流器、排水系统、风量调节器、风机、出风口、循环水箱、给水系统、排水管以及给水管组成。吸风口外接钢圈风

筒,因截割头高强度截割破碎产生的粉尘随风流受负压作用被吸入钢圈风筒,含尘风流进入风机后首先通过雾化组件,雾化组件由 2 层共 12 个均匀安装在内壁上的喷头构成,喷头扩散角度为 90°,以实现雾滴对内部风流通道的全覆盖;粉尘颗粒与雾滴相互碰撞一同进入旋流器中,旋流器叶轮在风流作用下被动旋转,拦截水雾和粉尘颗粒,水雾在叶轮上形

成水膜后增强对粉尘颗粒的拦截效果;粉尘和雾滴共同在旋流器中高速运动,强化了二者的碰撞、粘结,形成含尘液滴,增加了对粉尘的捕获率。旋流器叶片的旋转离心作用将附着其上的含尘液滴抛至机壳内壁上,落入积水盒;积水盒内的污水由排水系统排入循环水箱,过滤后由给水系统送入雾化系统循环利用,净化后的气体经通风机、出风口排出。



1—吸风口; 2—雾化系统; 3—积水盒; 4—旋流器; 5—排水系统; 6—风量调节器; 7—风机; 8—出风口; 9—循环水箱; 10—给水系统; 11—给水管; 12—排水管

图 7 KCS-500DZ 型矿用湿式除尘风机示意

Fig.7 Schematic of the wet dust removal fan (KCS-500DZ) using in coal mines

湿式除尘风机主要工作技术参数见表 1。机身距掘进工作面 30 m,以避免因风机吸风口、出风口距离过近而产生局部循环风;钢圈风筒的进风口距掘进工作面 2 m,风筒入口吸风量为 270 m³/min,是综掘面压入式通风量的 0.79 倍,既能够最大程度吸入含尘风流,又满足长压短抽式通风的设计原则^[23]。压入式风筒出风口距综掘面 5 m,保证综掘面风量风速要求的同时避免与除尘风机排风口距离过近产生循环风。

表 1 KCS-500DZ 型矿用湿式除尘风机主要技术参数

Table 1 Main technical parameters of the wet dust removal fan (KCS-500DZ) using in coal mines

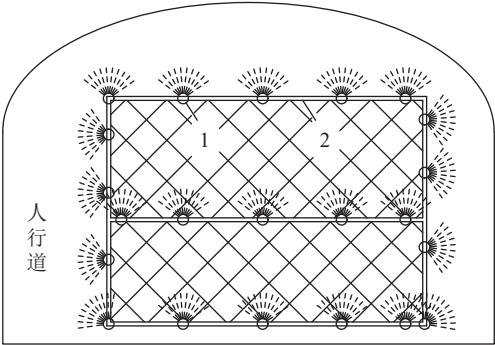
最大处理 风量/(m ³ ·min ⁻¹)	工作 阻力/Pa	额定 功率/kW	额定 电压/V	水压/MPa	质量/kg
500	1 200	22*2	660/1 140	0.6	1900

3.2 风幕控尘与感应式全断面水幕帘隔尘

综掘面所需压入式供风风量为 340 m³/min,略大于除尘风机风筒入口吸风量,少部分含尘风流无法完全被除尘风机吸入而向巷道后方运移,因此在压入式风筒上距综掘面 10 m 处装设一个旋流器用于产生风幕,控制粉尘的运移范围。掘进机不截割时关闭旋流器出风口。

为进一步降低掘进巷道空气中的粉尘含量,在距离综掘面 40 m 处设置一道感应式水幕帘和防尘滤网,如图 8 所示。水幕供水的开启和关闭由自动控制器根据在线粉尘浓度测试仪上的浓度值控制,

当截割作业或钻孔作业开始时,巷道内粉尘浓度增加,水幕帘自动开启,喷头扩散角为 90°,间隔为 0.6 m。安设于防尘滤网中部和下部的喷头向防尘网喷射,用于形成含水膜的水幕帘。安设于防尘滤网上端的喷头向巷道顶板喷射,安设于人行道一侧的雾化喷头同时由红外感应器控制向人行道侧帮喷射,当作业人员通过时自动关闭喷头,保障工作人员舒适度,雾滴喷射方向朝向掘进工作面 30°以抵抗风流的影响,增加雾滴和粉尘颗粒的碰撞几率与拦截效果。



1—雾化喷头; 2—输水管

图 8 感应式水幕帘和防尘滤网示意

Fig.8 Automatic control water curtain and dust filter diagram

3.3 综合降尘效果分析

为了测定采用综合降尘措施后的降尘效果,在掘进机司机处和机身后 5 m 处的回风侧各设置一个测尘点;由于全尘和呼尘质量浓度在距离掘进工作面约 40 m 以后将基本保持不变^[24],因此在防尘帘后方 2 m 处增设一个测尘点,粉尘采样器固定高度为

作业人员呼吸带高度,即 1.5 m,滤膜直径为 37 mm。采用综合降尘措施后,掘进机司机处呼尘平均质量浓度降至 4 mg/m^3 ,降尘率达到 90.6%;全尘质量浓度降至 20.5 mg/m^3 ,降尘率达到 93.6%。从现场来看,司机前方能见度较低,后方视野则比较清晰,说明截割产生的粉尘被集中在距司机约 1 m 处的空间内,除尘风机和风幕共同作用,很好地阻止了粉尘向巷道中扩散。掘进机机身后 5 m 处的回风侧呼尘和全尘降尘率分别为 86.9% 和 91.5%,粉尘浓度高于司机处,这一现象是由于刮板输送机转运处碎煤块相互碰撞产生及二次扬尘所致。感应式全断面水幕帘隔尘效果明显,其后方 2 m 处呼尘和全尘平均质量浓度分别降至 2.4 mg/m^3 和 3.9 mg/m^3 ,降尘率分别达 91.3% 和 95.1%,实现了综掘面粉尘的高效治理。

4 结 论

1) 根据塑性区体积计算方法,截齿齿尖角度越小塑性区体积越小,据此提出减小掘进机截齿齿尖角度,降低截割作业时粉尘的产生量。

2) 在掘进现场实测掘进机司机呼吸带高度处的呼尘和全尘质量浓度,当截齿锥角减小、截割头转速降低后,截割产生的呼尘和全尘质量浓度都有显著降低。

3) 在减尘基础上,利用以掘进机外喷雾和湿式除尘风机为主、控尘风幕和感应式全断面水幕帘为辅的综合降尘措施,治理后掘进机司机处的全尘和呼尘平均质量浓度降低至 4 mg/m^3 和 20.5 mg/m^3 ,降尘率分别为 90.6% 和 93.6%;水幕帘后方 2 m 处呼尘和全尘平均质量浓度分别降低至 2.4 mg/m^3 和 3.9 mg/m^3 ,降尘率分别达 91.3% 和 95.1%。

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