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综掘工作面混合式风流调控下的粉尘沉降研究

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摘要: 煤矿掘进过程中粉尘聚集严重, 目前针对综掘工作面混合式风流调控下粉尘沉降规律及优化的研究还不够深入。基于混合式风流调控系统, 依托陕煤集团神木柠条塔矿业有限公司综掘工作面, 分析了压风口距工作面距离、压风口右偏角度、压风口口径、抽风口距工作面距离和压抽比等混合式风流调控参数对粉尘沉降规律的影响: 随着压风口距工作面距离增加, 司机处和回风侧行人呼吸带截面大颗粒粉尘占比先增后减再增, 小颗粒粉尘占比增加; 随着压风口右偏角度增加, 司机处和回风侧行人呼吸带截面大颗粒粉尘占比变化明显; 随着压风口口径增加, 司机处截面小颗粒粉尘占比先增后减再增, 回风侧行人呼吸带截面大颗粒粉尘占比先增后减; 随着抽风口距工作面距离增加, 司机处截面大颗粒粉尘占比先增后减, 小颗粒粉尘占比先增后减再增, 回风侧行人呼吸带截面粉尘粒径分布变化不大; 随着压抽比增大, 司机处和回风侧行人呼吸带截面小颗粒粉尘占比减小。以上述风流调控各参数为自变量, 回风侧行人呼吸带全尘平均浓度和司机处呼尘平均浓度最低为优化目标, 建立了粉尘沉降优化回归模型, 利用粒子群优化算法求解模型, 得到最优风流调控方案: 压风口距工作面距离为 8.9 m, 压风口右偏角度为 14.8°, 压风口口径为 0.9 m, 抽风口距工作面距离为 4.3 m, 压抽比为 1.1。搭建了风流调控下粉尘沉降实验平台, 实验结果表明: 测试值与粉尘沉降优化回归模型的模拟值误差在 13% 以内, 验证了模型的准确性; 优化后粒径为 71~100 μm 的粉尘受风流调控参数影响明显, 沉降在掘进机前方; 优化后回风侧行人呼吸带全尘平均浓度和司机处呼尘平均浓度分别降低了 47.4% 和 42.4%, 降尘效果明显。

关键词: 综掘工作面; 混合式通风; 风流调控; 粉尘沉降; 粉尘浓度

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Research on dust settlement under mixed air flow control in fully mechanized excavation face

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Abstract: Dust accumulation is severe during coal mine excavation. Currently, research on the dust settlement law and optimization under mixed air flow control in fully mechanized excavation faces is not in-depth enough. Based on a hybrid air flow control system and relying on the fully mechanized excavation face of Shaanxi Coal Group Shenmu Ningtiaota Mining Co., Ltd., the influence of mixed air flow control parameters such as the distance from the pressure air outlet to the working face, the right angle of the pressure air outlet, the pressure air outlet diameter, the distance from the extraction air outlet to the working face, and the pressure extraction ratio on the dust settlement law is analyzed. As the distance between the pressure air outlet and the working face increases, the proportion of large particle dust in the cross-section of the personnel breathing zone on the return air sides and

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the driver's location first increases, then decreases, and then increases again. The proportion of small particle dust increases. As the right deviation angle of the air inlet increases, the proportion of large particle dust in the personnel breathing zone section on the return air sides and the driver's location changes significantly. As the diameter of the air inlet increases, the proportion of small particle dust in the driver's location section first increases, then decreases, and then increases again. The proportion of large particle dust in the personnel breathing zone section on the return air side first increases and then decreases. As the distance between the extraction air outlet and the working face increases, the proportion of large particle dust at the driver's location section first increases and then decreases. The proportion of small particle dust first increases and then decreases and then increases again. The particle size distribution of dust at the personnel breathing zone section on the return air side does not change much. As the pressure-pumping ratio increases, the proportion of small particle dust in the cross-section of the personnel breathing zone on return air sides and the driver's location decreases. Taking the above air flow control parameters as independent variables, the average concentration of total dust in the personnel breathing zone on the return air side and the average concentration of exhaled dust at the driver's location are the optimization objectives. A dust settlement optimization regression model is established, and the particle swarm optimization algorithm is used to solve the model. The optimal air flow control scheme is obtained. The distance between the pressure air outlet and the working face is 8.9 meters, the right angle of the compressed air outlet is 14.8° , the diameter of the compressed air outlet is 0.9 meters, the distance between the extraction air outlet and the working face is 4.3 meters, and the pressure-pumping ratio is 1.1. The experimental platform for dust settlement under wind flow control is built. The experimental results show that the error between the test values and the simulated values of the dust settlement optimization regression model is within 13%, which verifies the accuracy of the model. The optimized dust with particle sizes of $71\text{-}100 \mu\text{m}$ is significantly affected by the wind flow regulation parameters and settles in front of the roadheader. After optimization, the average dust concentration of total dust in the personnel breathing zone on the return air side and the average dust concentration at the driver's location decrease by 47.4% and 42.4%, respectively, indicating a significant dust reduction effect.

Key words: fully mechanized excavation face; mixed ventilation; air flow control; dust settlement; dust concentration

0 引言

随着我国煤炭产业机械化技术的发展,掘进过程中粉尘产生量越来越多,导致尘肺病发病率升高^[1-2]。在传统“通风总量”控制通风方式下,不能对压风口风流进行动态调控,使巷道内粉尘聚集严重,为改善该问题,国内外学者对粉尘场分布及沉降情况进行了大量研究。李雨成等^[3]研究了出风口参数变化对粉尘场分布规律的影响。蒋仲安等^[4]等研究了风筒不同高度对粉尘场的影响,得到了距工作面20 m处粉尘浓度最低。陈绍杰等^[5]研究了风筒不同位置及不同压风口风速对粉尘悬浮运移规律的影响。Zhang Lichao等^[6]对综采工作面粉尘浓度和粒径空间分布规律进行了研究。M. M. Alam^[7]、K. J. Candra等^[8]利用数值模拟分析了粉尘颗粒的基本分布规律。王建国等^[9]研究了风流影响下粉尘浓度分布情况及粉尘沉降规律。王晓珍等^[10]分析了压入式通风下粉

尘浓度分布,得到全尘和呼尘浓度沿程变化规律。秦跃平等^[11]、Wang Zhongwei等^[12]通过数值模拟分别研究了压入式和混合式通风下的粉尘团逸散情况,得到了粉尘沿程分布规律。王冕^[13]通过相似模拟实验研究了压入式通风方式下粉尘沉降规律。龚晓燕等^[14-16]研发了风流动态调控装置并研究了压风口口径、偏角对粉尘运移的影响。上述研究分析了工作面风流对粉尘场分布及沉降规律的影响,但对综掘工作面混合式风流调控下粉尘沉降规律及优化的研究还不够深入。

本文以陕煤集团神木柠条塔矿业有限公司(以下简称柠条塔煤矿)综掘工作面为背景,研究压风口距工作面距离、右偏角度、口径、抽风口距工作面距离和压抽比等混合式风流调控参数对粉尘沉降规律的影响,以及参数综合变化下粉尘沉降的最优风流调控方案。研究结果可为改善煤矿井下作业环境提供新思路。

1 风流调控下粉尘沉降的有限元模型建立

1.1 混合式风流调控系统布局

对柠条塔煤矿综掘工作面传统的混合式通风方式进行改造,在压风筒出风口处安装风流调控装置,混合式风流调控系统布局如图1所示^[17],通过改变出风口风流参数改变风流状态,进而研究粉尘沉降规律并对粉尘场进行优化。

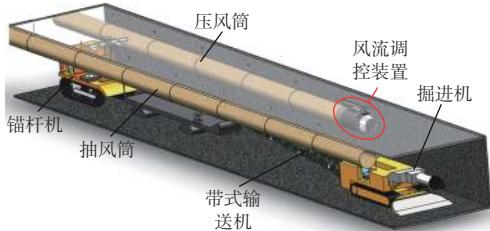


图1 混合式风流调控系统布局

Fig. 1 Layout of hybrid air flow control system

1.2 几何模型建立及网格划分

根据综掘工作面巷道端面尺寸及井下相关设备等参数,建立混合式风流调控下粉尘沉降分析的几何模型,如图2(a)所示,其中X为巷道宽,Y为巷道高,Z为巷道长。模型为30 m×5.2 m×3.85 m(长×宽×高)的矩形巷道,压风筒、抽风筒直径均为1 m,中轴线距底板3.05 m,距侧壁0.7 m。将建立的几何模型进行网格划分,如图2(b)所示。

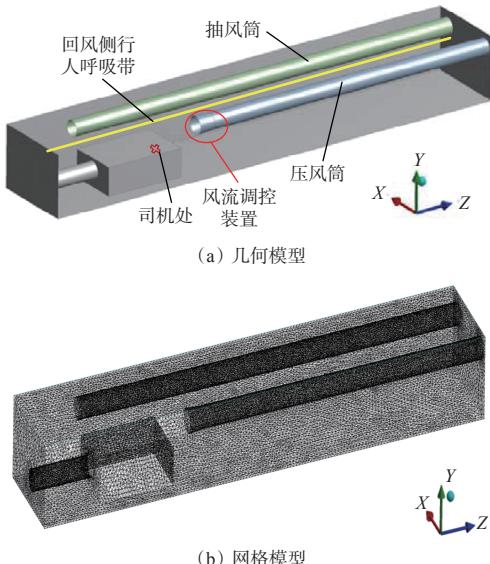


图2 粉尘沉降分析有限元模型

Fig. 2 Finite element model for dust settlement analysis

1.3 边界条件及模拟参数设定

研究粉尘在风流中的运动过程属于气固两相流理论,巷道内风流为湍流流动,因此选用Realizable k-ε模型^[18]。由于综掘工作面粉尘颗粒体积分数低于10%,属于稀相流动,所以选用Euler-Lagrange方法^[19]

来模拟计算。求解器采用瞬态和绝对速度进行求解,粉尘设定为形状规则的球形,产尘方式为面喷射,重力加速度为9.81 m/s²,粒径大小的分布遵循Rosin-Rammler分布^[20],通过现场实测确定粒径大小分布范围为1~100 μm。模型边界条件及离散相参数设定分别见表1、表2。

表1 边界条件

Table 1 Boundary condition

参数	设定
人口速度/(m·s ⁻¹)	9.78
压风口	入口湍流强度/%
	2.97
	入口水力直径/m
	1.0
人口速度/(m·s ⁻¹)	-9.78
抽风口	入口湍流强度/%
	2.97
	入口水力直径/m
	1.0
入口边界类型	Velocity-inlet
出口边界类型	Outflow
壁面剪切条件	No Slip

表2 离散相参数

Table 2 Discrete phase parameters

参数	设定
相间耦合	On
相间耦合频率/(s ⁻¹)	20
升力	On
材质	Coal-mv
粒径个数	10
分布指数	1.62
质量流率/(kg·s ⁻¹)	0.004
积分尺度	0.15
湍流扩散模型	DRW模型
离散相边界类型	底板trap, 其余reflect

1.4 网格独立性检验

为确保数值模拟结果的准确性,需对网格独立性进行检验。在回风侧行人呼吸带($X=4.7\text{ m}$, $Y=1.5\text{ m}$, $Z=0\sim30\text{ m}$)上取10个点,比较其原始场(原始场工况:压风口距工作面10 m,偏转0°,口径为1 m,抽风口距工作面5 m,压抽比为1)计算的风速,取网格数量分别为 80.8×10^4 , 97.1×10^4 , 122.6×10^4 个,风速分布如图3所示。可看出当网格数量从 80.8×10^4 个增加到 122.6×10^4 个,风速在分布上差别不大,对于计算结果影响也很小。但网格数量不断增加,计算量也会增加,因此网格数量选用 80.8×10^4 个最佳。

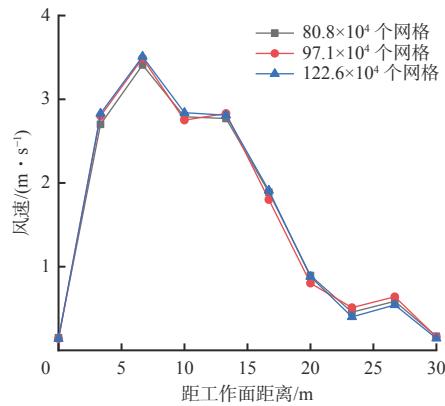
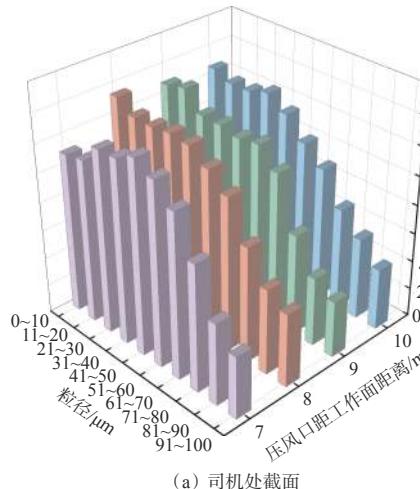


图3 不同网格数量下风速分布

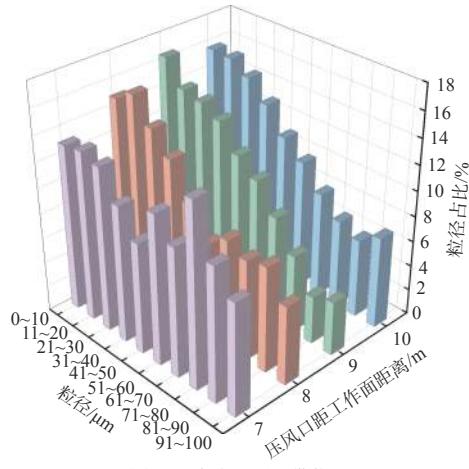
Fig. 3 Wind speed distribution under different grid numbers

2 风流调控单参数变化对粉尘沉降规律影响模拟分析

为研究风流调控单参数变化对粉尘沉降的影响规律,选取司机处($X=2.6\text{ m}$, $Y=2\text{ m}$, $Z=7.5\text{ m}$)和回风侧行人呼吸带截面,统计这2处粉尘粒径分布来反映粉尘沉降情况。



(a) 司机处截面



(b) 回风侧行人呼吸带截面

图4 压风口距工作面距离变化下粉尘粒径分布

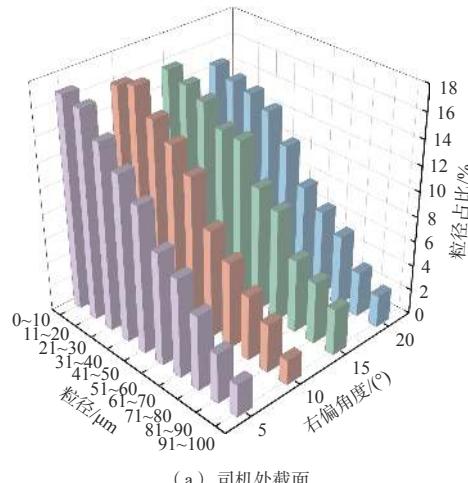
Fig. 4 Particle size distribution of dust under the change of distance between pressure air outlet and working face

2.1 压风口距工作面距离对粉尘粒径分布影响

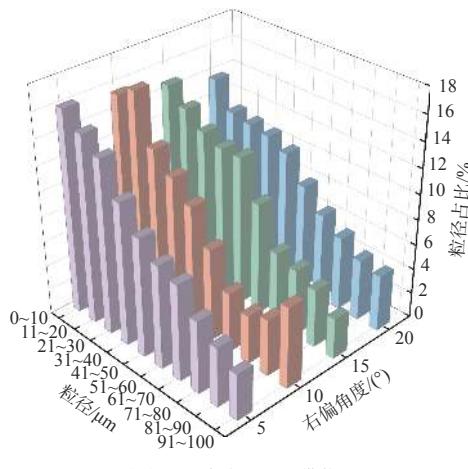
压风口距工作面距离分别为7, 8, 9, 10m时司机处和回风侧行人呼吸带截面粉尘粒径分布如图4所示。可看出随着压风口距工作面距离的增加,在司机处和回风侧行人呼吸带截面的大颗粒粉尘占比先增后减再增,较小颗粒的粉尘占比增加但变化不大;粒径为71~100 μm 的粉尘向下沉降明显,小颗粒粉尘占比有所增加。因此,在压风口距工作面距离为9m左右时,粉尘沉降效果最好。

2.2 压风口右偏角度对粉尘粒径分布影响

压风口右偏角度分别为5, 10, 15, 20°时司机处和回风侧行人呼吸带截面粉尘粒径分布如图5所示。可看出随着压风口右偏角度增加,压风口风流方向改变,在司机处截面大颗粒粉尘占比先减再增,在回风侧行人呼吸带截面的大颗粒粉尘占比先增后减再增;在压风口右偏角度为15°时,粒径为91~100 μm 的粉尘沉降明显,而小颗粒粉尘受风流影响较大,沉降不明显。因此,在压风口右偏角度为15°左右时,粉尘沉降效果最好。



(a) 司机处截面



(b) 回风侧行人呼吸带截面

图5 压风口右偏角度变化下粉尘粒径分布

Fig. 5 Particle size distribution of dust under the change of right angle of pressure air outlet

2.3 压风口口径对粉尘粒径分布影响

压风口口径分别为 0.8, 0.9, 1.0, 1.1 m 时司机处和回风侧行人呼吸带截面粉尘粒径分布如图 6 所示。可看出随着压风口口径的增加, 在司机处截面小颗粒粉尘占比先增后减再增, 回风侧行人呼吸带截面小颗粒粉尘占比变化不明显, 而大颗粒粉尘占比先增后减; 粒径为 81~100 μm 的粉尘沉降明显, 而在口径为 0.9 m 时粉尘占比波动很大, 其余口径时粉尘占比变化不明显。因此, 在压风口口径为 0.9 m 左右时, 粉尘沉降效果最好。

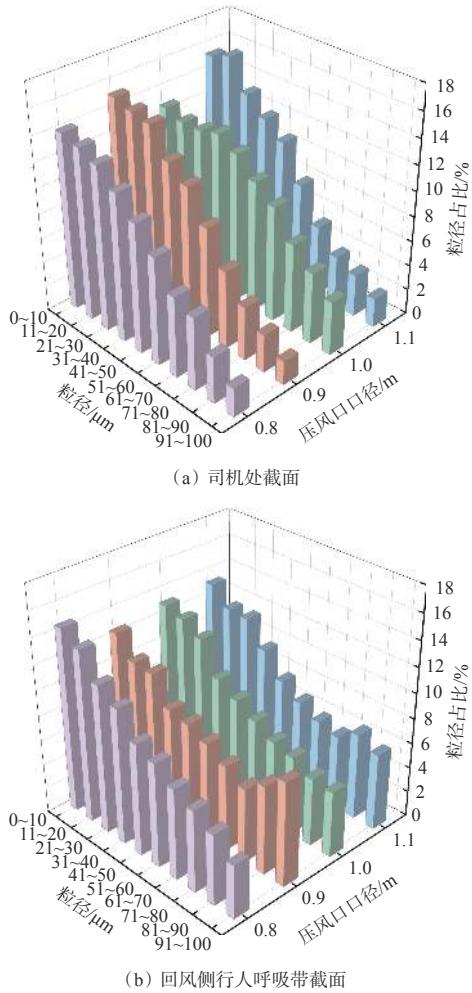


图 6 压风口口径变化下粉尘粒径分布

Fig. 6 Particle size distribution of dust under the change of pressure air outlet diameter

2.4 抽风口距工作面距离对粉尘粒径分布影响

抽风口距工作面距离分别为 2, 3, 4, 5 m 时司机处和回风侧行人呼吸带截面粉尘粒径分布如图 7 所示。可看出随着抽风口距工作面距离的增加, 司机处截面大颗粒粉尘占比先增后减, 小颗粒粉尘占比先增后减再增, 回风侧行人呼吸带截面粉尘粒径分布变化不明显; 粒径为 71~100 μm 的粉尘在抽风口距工作面 3~5 m 范围内沉降明显, 而小颗粒粉尘在

抽风口距工作面距离为 5 m 时占比增加幅度最大, 在抽风口距工作面距离为 3 m 时占比变化不大, 在抽风口距工作面距离为 4 m 时占比也有所增加, 且粉尘粒径分布较均匀。因此, 在抽风口距工作面距离为 4 m 左右时, 粉尘沉降效果最好。

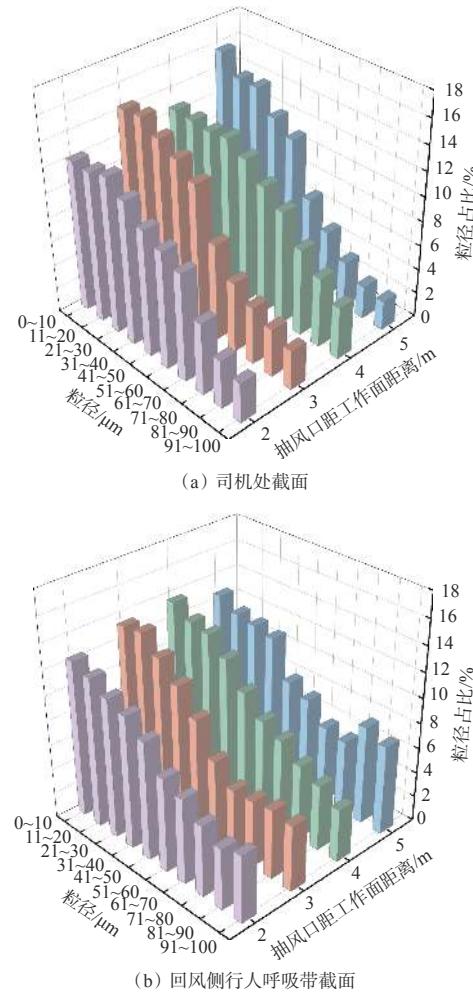


图 7 抽风口距工作面距离变化下粉尘粒径分布

Fig. 7 Particle size distribution of dust under the change of distance between extraction air outlet and working face

2.5 压抽比对粒径占比影响

压抽比分别为 1.0, 1.1, 1.2, 1.3 时司机处和回风侧行人呼吸带截面粉尘粒径分布如图 8 所示。可看出随着压抽比增大, 在司机处和回风侧行人呼吸带截面的大颗粒粉尘占比变化不大; 在压抽比大于 1.0 时, 粉尘沉降明显, 小颗粒粉尘占比减少。因此, 在压抽比大于 1.0 时, 粉尘沉降效果最好。

3 风流调控参数综合变化下粉尘沉降优化分析

3.1 试验方案设计和数据获取

由于风流调控各参数会对粉尘场产生交互影响, 所以对参数综合变化下粉尘沉降进行优化分析。设计二次回归中心组合试验, 选取压风口距工

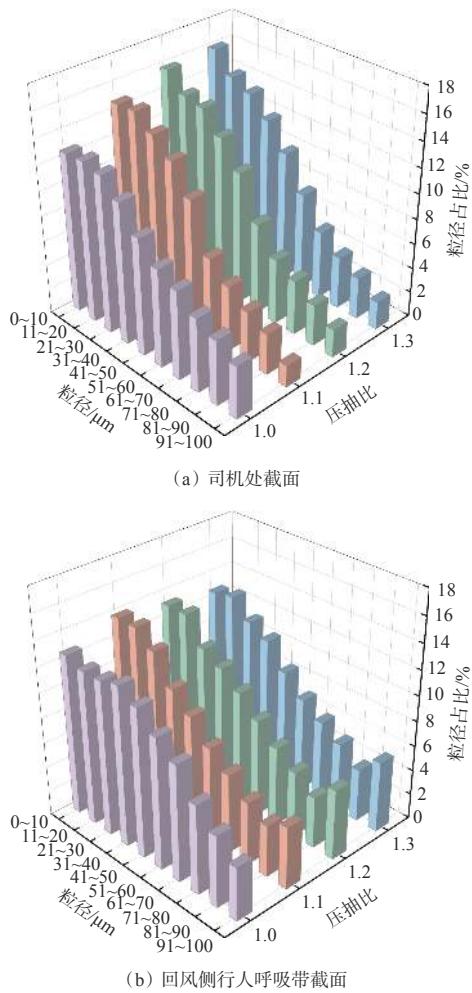


图 8 压抽比变化下粉尘粒径分布

Fig. 8 Particle size distribution of dust under the change of pressure-pumping ratio

作面距离 L_1 、抽风口距工作面距离 L_2 、压风口右偏角度 θ 、压风口口径 D 、压抽比 B 作为影响因素。选择五因素的上下水平并计算其零水平值与变化区间,五因素水平编码^[21]见表 3。其中 Z_i 为编码值, $+\gamma$ 为上星号臂, $-\gamma$ 为下星号臂, $+1$ 为上水平, 0 为零水平, -1 为下水平, Δi 为因素变化间距。

表 3 五因素水平编码

Table 3 Five factors horizontal coding

Z_i	L_1	L_2	θ	D	B
$+\gamma$	9.27	5.27	16.37	1.13	1.23
$+1$	9.00	5.00	15.00	1.10	1.20
0	8.00	4.00	10.00	1.00	1.10
-1	7.00	3.00	5.00	0.90	1.00
$-\gamma$	6.73	2.73	3.64	0.87	0.97
Δi	1.00	1.00	5.00	0.10	0.10

根据统计学原理,本试验采用五因素(1/2 实施)的二次回归中心组合设计,其中因素个数 $p=5$,试验实施情况 $\alpha=1$ 表示 1/2 实施,星号臂 $\gamma=1.27$,本文中

心试验点试验次数为 6,而全因素试验点和星号点由于因素搭配不同,按照设计方案进行试验,所以二水平($-1, 1$)全因素试验点个数 $m_c=16$,星号臂水平($-\gamma, \gamma$)因素试验点个数 $2p=10$,零水平试验点个数 $m_0=6$,共进行 32 组试验。试验设计方案及模拟计算结果见表 4。其中 X_1-X_5 分别对应 L_1, L_2, θ, D, B ; Y_1, Y_2 分别为回风侧行人呼吸带全尘平均浓度、司机处呼尘平均浓度^[22]。

表 4 试验设计方案及模拟计算结果

Table 4 Experimental design scheme and simulation calculation results

方案	X_1	X_2	X_3	X_4	X_5	$Y_1 / (\text{mg} \cdot \text{m}^{-3})$	$Y_2 / (\text{mg} \cdot \text{m}^{-3})$
1	1	1	1	1	1	130.754	83.474
2	1	1	1	-1	-1	137.729	84.821
3	1	1	-1	1	-1	153.503	81.955
4	1	1	-1	-1	1	135.773	80.676
5	1	-1	1	1	-1	135.552	95.461
6	1	-1	1	-1	1	143.223	83.555
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
31	0	0	0	0	0	114.552	60.282
32	0	0	0	0	0	125.330	62.133

3.2 粉尘沉降优化回归模型建立

将表 4 的回归样本数据利用 SPSS 软件进行平稳性检验,根据变量累积比例与指定分布累积比例之间关系绘制 P-P 图,验证数据近似符合正态分布且偏差值较小,可作为建立粉尘沉降优化回归模型的数据样本。建立回风侧行人呼吸带全尘平均浓度 Y_1 和司机处呼尘平均浓度 Y_2 的回归方程:

$$\begin{aligned} Y_1 = & 100.61 - 3.64X_1 - 1.73X_2 - 7.35X_3 - 0.78X_4 - \\ & 0.94X_5 + 1.33X_1X_2 + 1.07X_1X_3 + 1.22X_1X_4 - \\ & 0.78X_1X_5 + 0.099X_2X_3 + 2.75X_2X_4 + \\ & 0.85X_2X_5 - 5X_3X_4 - 0.55X_3X_5 - 1.86X_4X_5 + \\ & 9.14X_1^2 + 6.4X_2^2 + 20.37X_3^2 + 2.83X_4^2 + 2.86X_5^2 \quad (1) \end{aligned}$$

$$\begin{aligned} Y_2 = & 58.59 + 2.44X_1 - 3.01X_2 - 2.21X_3 - 0.032X_4 + \\ & 0.46X_5 - 0.92X_1X_2 + 0.58X_1X_3 - 0.45X_1X_4 - \\ & 4.4X_1X_5 + 0.89X_2X_3 + 1.5X_2X_4 + 3.1X_2X_5 - \\ & 0.18X_3X_4 - 1.23X_3X_5 + 0.43X_4X_5 + 5.2X_1^2 + \\ & 4.05X_2^2 + 13.59X_3^2 - 1.33X_4^2 + 3.31X_5^2 \quad (2) \end{aligned}$$

该回归方程需完成显著性水平检验,计算该回归方程的失拟项 F 和概率 P ,得到式(1)的 F 值为 3.63、 P 值为 0.016 0,式(2)中的 F 值为 6.18、 P 值为

0.001 8。 P 值均在 0.05 以下, 表明该回归方程回归性较好。

通过回归分析, 以回风侧行人呼吸带全尘平均浓度及司机处呼尘平均浓度最低为优化目标, 建立粉尘沉降优化回归模型:

$$\left\{ \begin{array}{l} \min Y(X) = \{Y_1, Y_2\} \\ \text{s.t. } X = [X_1 \ X_2 \ X_3 \ X_4 \ X_5] \\ X_1 \in (7, 10) \\ X_2 \in (2, 5) \\ X_3 \in (5, 20) \\ X_4 \in (0.8, 1.1) \\ X_5 \in (1, 1.3) \end{array} \right. \quad (3)$$

3.3 粒子群优化算法求解

粒子群优化算法具有易于实现、计算精度高、收敛速度快等优势, 被广泛应用于优化问题中^[23]。基于粒子群优化算法对优化回归模型进行求解, 设定粒子种群初始规模为 100, 最大迭代次数为 500, 惯性权值为 0.7, 学习因子为 2.05。计算求解获得优化回归模型的非劣解集, 结合 5 个参数可实现的调节范围, 确定最优风流调控方案: 压风口距工作面距离为 8.9 m, 压风口右偏角度为 14.8°, 压风口口径为 0.9 m, 抽风口距工作面距离为 4.3 m, 压抽比为 1.1。

3.4 优化前后粉尘沉降效果对比分析

对原始场和优化风流调控后粉尘沉降效果进行对比分析, 如图 9 所示。可看出调控前大颗粒粉尘占比较多, 沉降粒子较少, 且随风流运移到掘进机后方, 扩散污染范围较大; 调控后的粉尘沉降效果明显, 大部分沉降到底板, 扩散污染范围明显减小, 小颗粒粉尘随着风流运移到后方, 且较调控前粉尘浓度明显降低。

4 实验验证

4.1 实验平台搭建及测试方案建立

为验证最优风流调控方案的效果, 在“综掘工作

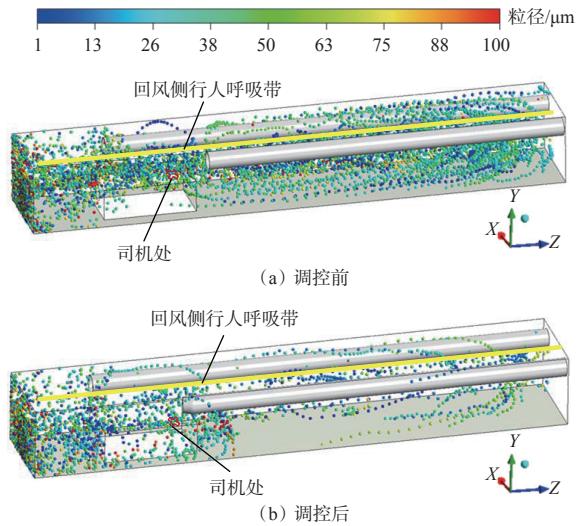


图 9 风流调控前后粉尘沉降效果对比

Fig. 9 Comparison of dust settling effect before and after air flow control

面风流智能调控降尘物理实验平台”^[24]的基础上, 搭建风流调控下粉尘沉降实验平台, 如图 10 所示。实验测点布置如图 11 所示, 在测点 1—7 布置全尘浓度传感器和 CCZ-1000 粉尘浓度测试仪, 在测点 8 布置呼尘浓度传感器。为减少误差, 进行 5 次重复测试, 求平均值。

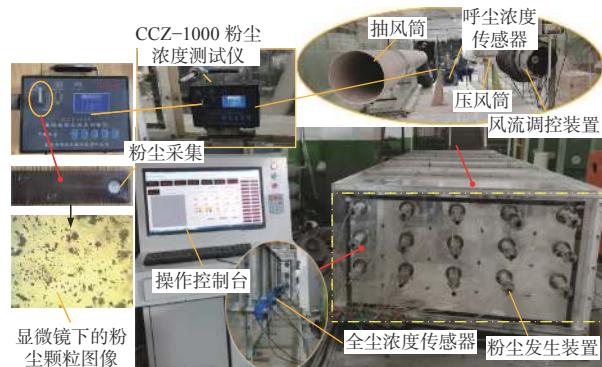


图 10 风流调控下粉尘沉降实验平台

Fig. 10 Dust settling experimental platform under air flow control

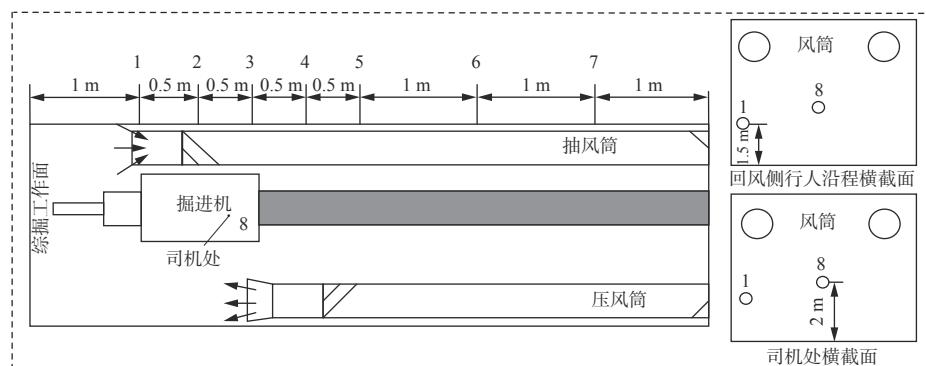


图 11 实验测点布置

Fig. 11 Experimental measuring point arrangement

4.2 实验结果分析

最优风流调控方案下回风侧行人呼吸带全尘平均浓度和司机处呼尘平均浓度的测试值与模拟值对比见表5。可看出测试值与模拟值的相对误差在13%以内,验证了粉尘沉降优化回归模型的准确性。

表5 最优风流调控方案测试值与模拟值对比

Table 5 Comparison of test values and simulated values of optimal air flow control scheme

位置	模拟值/(mg·m ⁻³)	测试值/(mg·m ⁻³)	相对误差/%
回风侧行人呼吸带	89.32	80.71	9.64
司机处	65.08	56.96	12.47

最优风流调控前后粉尘粒径分布如图12所示。可看出在风流调控优化后,71~100 μm 粉尘沉降效果显著,且在掘进机前方沉降;小于71 μm 的粉尘几乎不随风流向后扩散,小颗粒粉尘随风流的裹挟作用向后迁移,随着距工作面距离的增加,小颗粒粉尘占比增加。

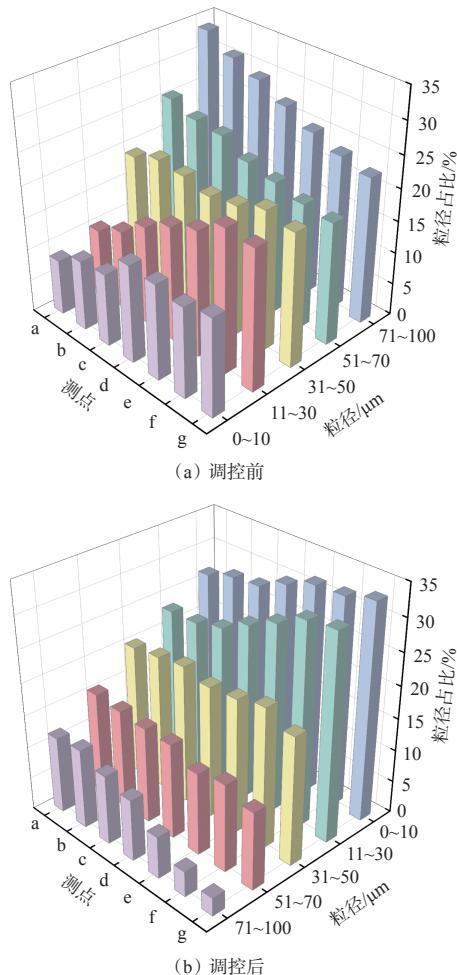


图12 风流调控前后粉尘粒径分布

Fig. 12 Particle size distribution of dust before and after air flow control

最优风流调控前后粉尘浓度如图13所示。可看

出经过风流调控优化后,回风侧行人呼吸带全尘平均浓度由调控前的156.6 mg/m³降低为82.4 mg/m³,降低了47.4%,司机处呼尘平均浓度由调控前的102.3 mg/m³降低为58.9 mg/m³,降低了42.4%。

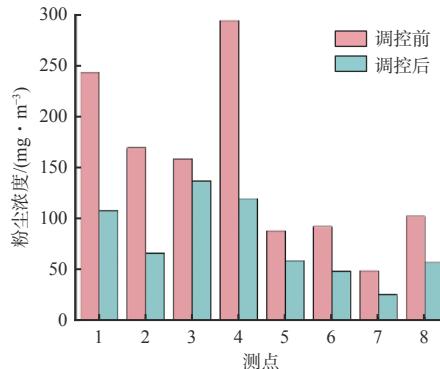


图13 风流调控前后粉尘浓度对比

Fig. 13 Comparison of dust concentration before and after air flow control

5 结论

1) 风流调控参数对粉尘沉降影响规律:随着压风口距工作面距离增加,司机处和回风侧行人呼吸带截面大颗粒粉尘占比先增后减再增,小颗粒粉尘占比增加;随着压风口右偏角度增加,司机处和回风侧行人呼吸带截面大颗粒粉尘占比变化明显;随着压风口口径增加,司机处截面小颗粒粉尘占比先增后减再增,回风侧行人呼吸带截面大颗粒粉尘占比先增后减;随着抽风口距工作面距离增加,司机处截面大颗粒粉尘占比先增后减,小颗粒粉尘占比先增后减再增,回风侧行人呼吸带截面粉尘粒径分布变化不大;随着压抽比增大,司机处和回风侧行人呼吸带截面小颗粒粉尘占比减小。

2) 以风流调控参数为自变量,以巷道内回风侧行人呼吸带全尘平均浓度和司机处呼尘平均浓度最低为目标,建立了粉尘沉降优化回归模型,通过粒子群优化算法求解,得到最优风流调控方案:压风口距工作面距离为8.9 m,压风口右偏角度为14.8°,压风口口径为0.9 m,抽风口距工作面距离为4.3 m,压抽比为1.1。

3) 经风流调控优化后,粒径为71~100 μm 的粉尘大部分在掘进机前方沉降,粒径小于71 μm 的粉尘随风流向后扩散,充满整个巷道;回风侧行人全尘平均浓度降低了47.4%,司机处呼尘平均浓度降低了42.4%。

参考文献(References):

- [1] 刘峰,曹文君,张建明,等.我国煤炭工业科技创新进

- 展及“十四五”发展方向[J]. 煤炭学报, 2021, 46(1): 1-15.
- LIU Feng, CAO Wenjun, ZHANG Jianming, et al. Current technological innovation and development direction of the 14^(th) Five-Year Plan period in China coal industry[J]. Journal of China Coal Society, 2021, 46(1): 1-15.
- [2] 程卫民, 周刚, 陈连军, 等. 我国煤矿粉尘防治理论与技术 20 年研究进展及展望[J]. 煤炭科学技术, 2020, 48(2): 1-20.
- CHENG Weimin, ZHOU Gang, CHEN Lianjun, et al. Research progress and prospect of dust control theory and technology in China's coal mines in the past 20 years[J]. Coal Science and Technology, 2020, 48(2): 1-20.
- [3] 李雨成, 李智, 高伦. 基于风流及粉尘分布规律的机掘工作面风筒布置[J]. 煤炭学报, 2014, 39(增刊 1): 130-135.
- LI Yucheng, LI Zhi, GAO Lun. Arrangement of air duct of tunneling working face based on the distribution laws of airflow and dust[J]. Journal of China Coal Society, 2014, 39(S1): 130-135.
- [4] 蒋仲安, 闫鹏, 陈举师, 等. 岩巷掘进巷道长压短抽通风系统参数优化[J]. 煤炭科学技术, 2015, 43(1): 54-58.
- JIANG Zhong'an, YAN Peng, CHEN Jushi, et al. Optimization on parameters of long distance forced and short distance exhausted ventilation system in mine rock heading roadway[J]. Coal Science and Technology, 2015, 43(1): 54-58.
- [5] 陈绍杰, 邱银鸽, 李改革. 压入式通风掘进巷道粉尘悬浮运移规律研究[J]. 煤矿安全, 2022, 53(4): 178-182, 192.
- CHEN Shaojie, QI Yingge, LI Gaige. Study on dust suspension law in driving roadway with forced ventilation[J]. Safety in Coal Mines, 2022, 53(4): 178-182, 192.
- [6] ZHANG Lichao, ZHOU Gang, MA Yu, et al. Numerical analysis on spatial distribution for concentration and particle size of particulate pollutants in dust environment at fully mechanized coal mining face[J]. Powder Technology, 2021(1): 143-158.
- [7] ALAM M M. An integrated approach to dust control in coal mining face areas of a continuous miner and its computational fluid dynamics modeling[D]. Carbondale: Southern Illinois University, 2006.
- [8] CANDRA K J, PULUNG S A, SADASHIV M A. Dust dispersion and management in underground mining faces[J]. International Journal of Mining Science and Technology, 2014, 24(1): 39-44.
- [9] 王建国, 周侗柱, 戚斐文, 等. 凉水井矿综采工作面粉尘运移规律数值仿真[J]. 西安科技大学学报, 2020, 40(2): 195-203.
- WANG Jianguo, ZHOU Tongzhu, QI Feiven, et al. Numerical simulation of dust movement rules at fully-mechanized mining faces in Liangshuijing Coal Mine[J]. Journal of Xi'an University of Science and Technology, 2020, 40(2): 195-203.
- [10] 王晓珍, 蒋仲安, 王善文, 等. 煤巷掘进过程中粉尘浓度分布规律的数值模拟[J]. 煤炭学报, 2007, 32(4): 386-390.
- WANG Xiaozhen, JIANG Zhong'an, WANG Shanwen, et al. Numerical simulation of distribution regularities of dust concentration during the ventilation process of coal roadway driving[J]. Journal of China Coal Society, 2007, 32(4): 386-390.
- [11] 秦跃平, 姜振军, 张苗苗, 等. 综掘面粉尘运移规律模拟及实测对比[J]. 辽宁工程技术大学学报(自然科学版), 2014, 33(3): 289-293.
- QIN Yueping, JIANG Zhenjun, ZHANG Miaomiao, et al. Comparison of simulation on dust migration regularity in fully mechanized workface[J]. Journal of Liaoning Technical University (Natural Science), 2014, 33(3): 289-293.
- [12] WANG Zhongwei, LI Shugang, REN Ting, et al. Respirable dust pollution characteristics within an underground heading face driven with continuous miner-a CFD modelling approach[J]. Journal of Cleaner Production, 2019, 217: 267-283.
- [13] 王冕. 掘进巷道流场结构及粉尘沉降规律相似模拟研究[J]. 矿业安全与环保, 2021, 48(3): 56-61.
- WANG Mian. Similar simulation study on the flow field structure and the law of dust settlement of heading roadway[J]. Mining Safety & Environmental Protection, 2021, 48(3): 56-61.
- [14] 龚晓燕, 樊江江, 刘壮壮, 等. 综掘面出风口及抽风口风流综合调控下粉尘场优化分析[J]. 煤炭学报, 2021, 46(增刊 2): 800-809.
- GONG Xiaoyan, FAN Jiangjiang, LIU Zhuangzhuang, et al. Optimization analysis of dust field under comprehensive control of air outlet and exhaust air flow in fully mechanized excavation face[J]. Journal of China Coal Society, 2021, 46(S2): 800-809.
- [15] GONG Xiaoyan, JIA Congcong, SUN Kang, et al. Distribution law and prediction model of dust concentration under airflow adjustment in fully mechanized heading face[J]. Mathematical Problems in Engineering, 2019(16): 1155-1172.
- [16] 龚晓燕, 费颖豪, 牛虎明, 等. 掘进面出风口风流与风幕调控下的粉尘分布响应曲面优化研究[J]. 中国安全生产科学技术, 2022, 18(12): 80-88.
- GONG Xiaoyan, FEI Yinghao, NIU Huming, et al. Study on response surface optimization of dust distribution under regulation of air flow and air curtain at air outlet of excavation face[J]. Journal of Safety

- Science and Technology, 2022, 18(12): 80-88.
- [17] 龚晓燕,侯翼杰,赵宽,等.综掘工作面风筒出风口风流智能调控装置研究[J].煤炭科学技术,2018,46(12):8-14.
GONG Xiaoyan, HOU Yijie, ZHAO Kuan, et al. Study on intelligent control device for airflow of air duct outlet in fully-mechanized heading face[J]. Coal Science and Technology, 2018, 46(12): 8-14.
- [18] 王福军.计算流体动力学分析——CFD软件原理与应用[M].北京:清华大学出版社,2004.
WANG Fujun. Computational fluid dynamics analysis - principle and application of CFD software[M]. Beijing: Tsinghua University Press, 2004.
- [19] 蒋仲安,张中意,谭聪,等.基于数值模拟的综采工作面通风除尘风速优化[J].煤炭科学技术,2014,42(10):75-78.
JIANG Zhong'an, ZHANG Zhongyi, TAN Cong, et al. Optimization on air velocity for ventilation and dust control of fully-mechanized coal mining face based on numerical simulation[J]. Coal Science and Technology, 2014, 42(10): 75-78.
- [20] 熊攀,鄢曙光.基于Rosin-Rammler函数的数值模拟对旋风除尘器粒径分布规律的研究[J].粉末冶金工业,2019,29(2):29-32.
XIONG Pan, YAN Shuguang. Numerical simulation of particle size distribution of cyclone dust collector based on Rosin-Rammler function[J]. Powder Metallurgy
- ~~~~~
- (上接第105页)
- [16] 姜子豪,胡友彪,琚棋定,等.矿井突水水源判别方法[J].工矿自动化,2020,46(4):28-33.
JIANG Zihao, HU Youbiao, JU Qiding, et al. A discrimination method of mine water inrush source[J]. Industry and Mine Automation, 2020, 46(4): 28-33.
- [17] 闫鹏程,尚松行,张超银,等.改进BP神经网络算法对煤矿水源的分类研究[J].光谱学与光谱分析,2021,41(7):2288-2293.
YAN Pengcheng, SHANG Songxing, ZHANG Chaoyin, et al. Classification of coal mine water sources by improved BP neural network algorithm[J].
- Industry, 2019, 29(2): 29-32.
- [21] 笪强.联合收割机脱粒装置分析及优化设计[D].西安:西安理工大学,2021.
DA Qiang. Analysis and optimization design of threshing device for combine harvester[D]. Xi'an: Xi'an University of Technology, 2021.
- [22] 龚晓燕,童丹丹,樊江江,等.综掘面风流调控下粉尘双目标优化研究[J].中国安全科学学报,2022,32(4):44-50.
GONG Xiaoyan, TONG Dandan, FAN Jiangjiang, et al. Study on dual-objective optimization of dust under airflow regulation in fully mechanized faces[J]. China Safety Science Journal, 2022, 32(4): 44-50.
- [23] 彭娟,程健,韩仿仿,等.基于粒子群算法的自动配煤系统多目标优化[J].工矿自动化,2009,35(10):25-28.
PENG Juan, CHENG Jian, HAN Fangfang, et al. Multi-target optimization for automatic blending coal system based on PSO algorithm[J]. Industry and Mine Automation, 2009, 35(10): 25-28.
- [24] 龚晓燕,赵少龙,刘壮壮,等.掘进面风流监测及适应性智能调控系统研制[J].安全与环境学报,2023,23(2):424-434.
GONG Xiaoyan, ZHAO Shaolong, LIU Zhuangzhuang, et al. Development of airflow monitoring and adaptive intelligent control system for heading face[J]. Journal of Safety and Environment, 2023, 23(2): 424-434.
- ~~~~~

- Spectroscopy and Spectral Analysis, 2021, 41(7) : 2288-2293.
- [18] XUE Jiankai, SHEN Bo. A novel swarm intelligence optimization approach: sparrow search algorithm[J]. Systems Science & Control Engineering, 2020, 8(1) : 22-34.
- [19] 李光阳,潘家文,钱谦,等.融合学习机制的多混沌麻雀搜索算法[J].计算机科学与探索,2023,17(5):1057-1074.
LI Guangyang, PAN Jiawen, QIAN Qian, et al. Multi-chaotic sparrow search algorithm based on learning mechanism[J]. Journal of Frontiers of Computer Science and Technology, 2023, 17(5): 1057-1074.