



Mechanisms of dust diffuse pollution under forced-exhaust ventilation in fully-mechanized excavation faces by CFD-DEM



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ABSTRACT

In order to investigate the diffuse pollution mechanisms of high-concentration dusts in the working regions of fully-mechanized excavation faces under forced-exhaust ventilation, a CFD-DEM airflow–dust coupled simulation approach was developed based on k – ϵ two-equation turbulent model and the Hertz–Mindlin model. The diffuse pollution characteristics of the dust particles with different sizes were analyzed by combining on-site measurements with simulation. Results show that, in the region 0–15 m away from the heading face, a large horizontal-vortex field was formed due to the effect of forced jet field. Under the airflows' drag force, the dust flows were stratified in a dense strip pattern, among which the larger dust particles flew zonally at lower heights. The airflow drag force dominated the movements of the dusts with a diameter range of 2.5–20 μm , while gravity significantly affected the diffusion of the dusts with a diameter range of 40–80 μm . The final dust emission ratio approximately decreased linearly with the increase of dust particle size. Large dust particles were more easily settled. Specifically, the dust particles with a diameter range of 7–20 μm showed long sedimentation regions, while the other dusts were intensively settled at around the head-on region. In addition, the dust particles with a diameter range of 2.5–7 μm showed stable passing ratios during the diffusion process, and the average z value presented non-significant decrease. Finally, the dust emission ratio of 2.5 μm reached as high as 63.4% due to the absorption of the negative pressure. Therefore, comprehensive dustproof measures should be taken by considering the diffuse pollution characteristics of dusts.

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1. Introduction

High-concentration dust in fully-mechanized excavation faces has been a challenging issue that hinders the safe and efficient coal excavation. According to measured data, without any dust prevention measures, the concentration of head-on dust in an excavation face, especially in a fully-mechanized excavation face, can exceed 3000 mg/m^3 . Driven by the airflows, the head-on dusts produced during coal cutting process can be spread and transported to the other regions, leading to high dust concentrations in various regions of the excavation face. According to the notification by the National Health and Family Planning Commission of PRC, the cumulative number of occupational disease cases in China was as high as 863,634 by 2014, of which 777,173 were pneumoconiosis cases, accounting for 89.99% of the total occupational disease cases in China. In 2014, there were 26,873 newly reported pneumoconiosis

cases in China, accounting for 89.66% of the new occupational disease cases. The workers in coal mining and some mining-supporting industries were at particularly high risks of pneumoconiosis, who accounted for 94.21% of the newly added pneumoconiosis cases [1–3]. Evidently, the high-concentration dusts have caused severe harm to the workers in mining-related industries. Fig. 1 shows the cumulative numbers of occupational disease cases and pneumoconiosis cases in China in the period of 2005–2014, and Fig. 2 shows the newly added numbers of the general pneumoconiosis cases and pneumoconiosis cases related to coal mining in China over the past decade. It is predicted that the pneumoconiosis cases in China will keep rising in the coming 10–15 years [4–5].

In addition, the high-concentration dusts reduce the equipment's service life and measurement precision and meanwhile lead to a low visibility in the excavation face. The fully-mechanized excavation faces are among coal mine working locations that impose the most severe occupational hazards [6–8]. Therefore, the investigation on the diffuse pollution mechanisms of the dusts in the fully-mechanized excavation face helps to lay essential theoretical and technological foundations for the improvement of dust prevention and treatment techniques.

Three common methods, field measurement, numerical simulation and experimental test, have been widely adopted by international researchers to investigate the diffusion rules of coal dusts. The field

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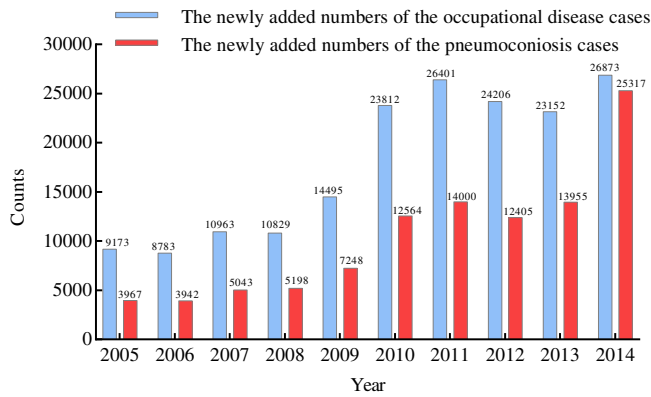


Fig. 1. The cumulative numbers of the occupational disease cases and pneumoconiosis cases.

measurements are vulnerable to on-site production conditions; moreover, the data acquisition method is generally unstable and the acquired data are far from comprehensive. Numerical simulation is subject to inaccuracies in dealing with the mathematical model and boundary conditions. By means of experimental test, scholars mainly conducted similarity experiments on the models with simple ventilating conditions and system structures and resulted in certain deviations from the site practical conditions [9–10]. Therefore, in the present work, the diffuse pollution mechanisms of dusts under forced-exhaust ventilation conditions were investigated by both numerical simulation and field measurement. Since numerical simulation shows strong operability and field measurements can verify the simulation results, the combination of these two method hope to provide some accurate and useful results.

Over the past years, researchers have performed extensive studies on the diffusion of coal dusts in both theoretical and practical aspects. Nakayama et al. conducted simulations on the migration of airflows in a fully-mechanized excavation face and the numerical results of airflow velocity were close to the measured data. However, the maximum airflow velocity at the cross section was larger than the measured data [11]. By combining field tests and numerical simulations, J. Toraño investigated the migration behaviors of airflows and airborne dusts flowing through a 14.7 m² cross section under forced-exhaust ventilation condition in a fully-mechanized excavation face [9]. Through a case study in China, Shengyong Hu et al. obtained the temporal and spatial distribution of respirable dusts after blasting in coal tunnel driving faces using direct simulation Monte Carlo (DSMC) method [12]. K. J. Candra et al. studied the dust diffusion and management in an excavation face using computational fluid dynamics (CFD) approach

[13]. Numerical simulations were commonly used for investigating dust diffuse pollution behaviors in coals in previous studies and some useful achievements were gained. However, a series of factors, including extremely small particle sizes and ultra large amount of coal particles, result in huge computation load which can go beyond the capability of even modern computer clusters [13–14]. Therefore, most simulations are limited to the macro-scale analysis of dust diffuse pollution, and the analysis of the motion characteristics of dust particles in air flow field at micro-scale still remains challenging.

At present, the calculation approaches of fluid–solid coupling fall into three categories: the Euler–Euler method (both fluid and solid are considered as continuous media), the Euler–Lagrange method (fluid is considered as continuous medium, but particles are considered as discrete media) and the Lagrange–Lagrange method (both fluid and solid are considered as discrete media). The Euler–Euler method, based on continuum mechanics, is a typical “phenomenological” approach, and the basic framework follows Biot consolidation theory. The motion of particles is described by Navier–Stokes equations, and the inconsistencies between the particle and fluid characteristics are simulated by a large number of modified equations, which makes the solution lack of theoretical basis. On the other hand, the Euler–Lagrange method, a mechanism model, is increasingly widely used in the simulation of two-phase fluid–solid flow since it can accurately reflect the airflow–dust coupling characteristics [15–18]. In this study, the discrete element method (DEM) was adopted in the calculation of dust particles. Based on the force analysis of the dust particles in the airflow filed, the forces which significantly contributed to the motion of individual particle were included into the mathematical model. Furthermore, the motion of particles in the airflow filed was tracked in real-time and the motion information was accurately extracted. The diffusion characteristics of dusts, including the constraint force from airflow, the spatial distribution, the motion path and the along-the-way settling behaviors of dusts, were analyzed at micro scale. In the present work, the 3_{down} 905 fully-mechanized excavation face of Jiangzhuang Coal Mine was taken as a study case. According to the actual measurement, the dust concentration in the head-on region of the fully-mechanized excavation face was higher than 1200 mg/m³ without any dustproof measures. Such a high concentration of dusts can spread and pollute the tunnel more than 300 m away from the head-on face, posing a serious threat to the health of miners. To solve this problem, simulations were performed by using CFD-EDM coupled approach based on the actual working conditions for the 3_{down} 905 fully-mechanized excavation face of Jiangzhuang Coal Mine. Furthermore, the simulation results were verified by the field measurement results for uncovering the diffuse pollution mechanisms of airborne dusts under forced-exhaust ventilation at micro-scale.

2. CFD simulation on airflows

There exist multiple factors that affect the motion of dusts, among which airflow's carrying effect is most remarkable. Therefore, the simulation results of airflow field determine the accuracy of the dust motion calculation. In this study, the airflow was simulated as a continuous phase based on the Euler model.

2.1. Modelling of airflow field

There are many models to describe the wind turbulent flow in the fully-mechanized excavation face, such as zero-equation model, one-equation model, two-equation model, Reynolds stress model and direct numerical simulation method. High Reynolds-number $k-\varepsilon$ model is the most common two-equation model, which is also a typical mathematical treatment of Eulerian method. The Reynolds number in the fully-mechanized excavation face exceeds 1×10^6 and thus the $k-\varepsilon$ turbulent model can favorably reflect the characteristics of airflow field [19–21].

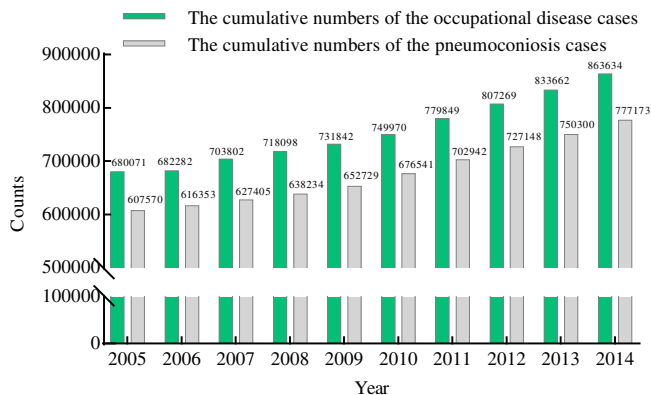


Fig. 2. The newly added numbers of the general pneumoconiosis cases and pneumoconiosis cases related to coal mining.

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