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# The effects of the pressure outlet's position on the diffusion and pollution of dust in tunnel using a shield tunneling machine

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ABSTRACT

In order to gain a more in-depth knowledge of a shield machine's dust-suppression ventilation system, this paper uses the shield region on the south side of the No. 8 Subway from Jiaodong International Airport, Qingdao, China, as a case study, and conducts field measurements and numerical simulations for examining dust concentration distributions in a tunnel when the ventilation system is not in operation (i.e., under single-pressure conditions) and when the air pressure cylinder is in operation (specifically, the distance between the pressure outlet-2 and the cutter, denoted as $L_p$, was set at different values within a range of 30~75 m). The results reveal that under single-pressure conditions, dust was diffused throughout the entire tunnel and caused serious pollution. After the ventilation system was opened: when $L_p < 50$ m, the use of a ventilation system could not control the diffusion of dust effectively, and its dust-suppression performance was enhanced with the increase of $L_p$; when 50 m $\leq L_p \leq 55$ m, its dust suppression performance was relatively optimal, but some dust still spread to the operating region; when $L_p > 70$ m, a low-velocity airflow belt was formed in the operating range of 25~30 m, i.e., the ventilation requirements could not be satisfied; and when 60 m $\leq L_p \leq 70$ m, both the ventilation and optimal dust suppression performance could be achieved simultaneously.

## 1. Introduction

A shield tunneling machine is a specific type of engineering machinery used for tunneling. Currently, in their design and manufacture stages, shield tunneling machines are always customized in accordance with different geological conditions, for which extremely high requirements regarding reliability are set [1].The ventilation system for dust removal is a key back-up system in a shield tunneling machine, and plays a crucial role in guaranteeing the safety of operators, the normal operation of electromechanical devices and the control of hazardous substances such as dust in the tunnel. Through the use of the ventilation system, fresh air is transported to the operating area, and simultaneously, both dust and hazardous gases produced in the shield tunneling process are discharged [2]. This has a direct impact on the operators' physical health and safety [3]. Therefore, gaining a more in-depth knowledge of the dust-removal ventilation systems in shield tunneling machines is of great significance.

Currently, researchers mainly adopt the following three methods for examining the ventilation system in a shield tunneling machine: field measurement; numerical simulation; and experimental measurement. Due to the limitations that occur when a tunnel is being constructed, it is difficult to use the field measurement method, and results from experimental measurements generally display a certain one-sidedness, as the parameters involved are always set specifically. In contrast, numerical simulations have a number of advantages, such as a high degree of visualization, low cost and easy operation, and have been applied extensively in related studies. Moreover, the actual operating process in a tunnel is quite complex and involves a number of uncontrollable factors; therefore numerical simulations are more suitable for the present study. [4–9]

Many researchers have conducted a large number of numerical simulations based on computational fluid dynamics (CFD) in order to investigate ventilation and dust suppression systems in underground spaces, such as tunnels, and have gained some useful results.

For example, Hu firstly established a numerical model of a tunnel's dust-removal ventilation system, and then investigated the ef-

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fects of certain parameters, such as the position of the pressure outlet and exhaust inlet, as well as the pressure-to-exhaust airflow rate ratio, all of which can provide important theoretical foundations for the design of a ventilation system for use in practical applications [10]. Furthermore, Guo et al. combined numerical simulations and field measurements for examining the control of dust that was generated during operations in the Zhongtianshan Tunnel, and developed some distribution rules of dust in the operating segment of a tunnel under construction. Their research results could act as a guide for dust suppression in the actual construction of a tunnel [11,12]. Xia et al. focused on the ventilation conditions from the main ventilation position in a tunnel's working face, and determined the optimal distance between the main pressure outlet and the front-end of the tunnel for achieving the most favorable ventilation performance [13,14]. Wang et al. performed numerical research on the movement and distribution of dust in a tunnel under construction when a mixing ventilation system was used. They then developed some movement and distribution rules of dust particles in the tunnel, and found that a far-pressure-near-absorption (FPNA) ventilation system was superior to other ventilation systems with regard to ventilation and dust-suppression performances under certain special circumstances [15]. Geng et al. conducted a numerical analysis on the dispersion condition of dust in a simplified tunnel using a mixing ventilation system, and ascertained the distribution and processing conditions of different sized dust particles in the tunnel [16–19]. Li et al. used CFD-based numerical simulations to explore the minimum ventilation requirements in very large underground engineering projects, and suggested that a minimum airflow velocity of 0.15 m/s can satisfy the requirements of oxygen supply, dust suppression and temperature control in a working face [20]. Finally, J. Toraño et al. also conducted CFD-based numerical simulations for investigating the evolution behaviors of airflows and dust in an excavation tunnel, and optimized the pressure and exhaust airflow rates, the position of the pressure outlet and exhaust inlet, as well as the arrangement of the ventilation system in the tunnel [21–24]. As stated above, researchers have performed a number of insightful studies on ventilation and dust suppression techniques in a tunnel; however, the models they used were over-simplified. In particular, for tunnels being constructed using shield machines, the ventilation models and dust-producing mechanisms display certain differences, and the systematical investigations on the effect of the pressure outlet's position on the pollution and diffusion of dust in a tunnel being constructed using a shield machine are still unknown; i.e., the related research results cannot be applied directly to a tunnel being constructed using a shield machine.

This study focuses on the dust-removal ventilation system in the shield zone on the south side of No. 8 Ø6.3 subway, and analyzes the ventilation model and dust-producing mechanisms when the shield machine is in operation [25–27]. Firstly, the current model was improved based on previous research, and a full-scale [28–31], three-dimensional (3D) model was established using the Solidworks platform (2011); then, using FLUENT software, the pollution and diffusion behaviors of dust in the tunnel being constructed using a shield machine, when the pressure outlet was set at different positions, were investigated; finally, the appropriate position range of the pressure outlet that can achieve a favorable dust suppression performance was derived. The present study will hopefully provide scientific and theoretical support for ventilation and dust removal in tunnels that are constructed using shield tunneling machines.

## 2. The establishment of a mathematical model

In this study, the mathematical model of single-phase airflow in a tunnel under construction was established based on the k-$\varepsilon$ double-equation model in the Eulerian method; then, in accordance with the two-phase flow behaviors of gas and dust particles, the Eulerian–Eulerian and Eulerian–Lagrangian methods were employed for establishing the k-$\varepsilon$-$\Theta$-$\mathrm{k_p}$ mathematical model and thereby exploring the dust diffusion rules in a space. In a tunnel under construction, the airflow-dust two-phase flow is generally in a turbulent state. Therefore, the established k-$\varepsilon$-$\Theta$-$\mathrm{k_p}$ mathematical model includes the turbulence model after the Reynold average Navier–Stokes on the gas-phase and particle-phase. [32–36] where the physical parameter, $\Phi$, obeyed the following principle:

$$\Phi = \bar{\phi} + \Phi',\ \overline{\Phi'} = 0,\ \overline{\bar{\phi}\Phi'} = 0,\ \bar{\phi}' = \bar{\phi},\ \bar{\bar{\phi}} = \bar{\phi} \tag{1}$$

For convenience, hereinafter it is assumed that $\phi = \bar{\phi}$.

The two-phase control equation of the turbulent gas-phase and turbulent particle-phase can be written as:

The continuity equation of the gas phase can be written as:

$$\frac{\partial(\alpha\rho)_q}{\partial t} + \frac{\partial(\alpha\rho U_i)_q}{\partial x_i} = -\frac{\partial}{\partial x_i}\left[\overline{(\alpha\rho)'_q U'_{i,q}}\right] \tag{2}$$

where $q$ denotes the gas phase; $\alpha$ denotes the volume fraction of the gas phase in the control volume; $U$ is the velocity, with a unit of m/s; $t$ denotes the time, with a unit of s; and $i$ is the indicator sign of the tensor, with a value range of (1, 2, 3).

The continuity equation of a particle's pycnometer density can be written as:

$$\frac{\partial(\alpha\rho)_p}{\partial t} + \frac{\partial(\alpha\rho U_i)_p}{\partial x_i} = -\frac{\partial}{\partial x_i}\left(\overline{(\alpha_p\rho_p)'U'_{i,p}}\right) \tag{3}$$

The gas-phase momentum equation can be written as:

$$\begin{aligned}\frac{\partial\left(\alpha\rho U_j\right)_q}{\partial t} + \frac{\partial\left(\alpha\rho U_i U_j\right)_q}{\partial x_i} &= -\alpha_q\frac{\partial P}{\partial x_j} + \alpha_q\rho_q g_j + \frac{\partial\tau_{i,j}}{\partial x_i}\\ &\quad + \beta_j\left(\{U_{j,p} - U_{j,q}\right) - \frac{\partial}{\partial x_i}\left(\alpha_q\rho_q\overline{U'_{i,q}U'_{j,p}}\right)\end{aligned} \tag{4}$$

$$\tau_{i,j} = \mu_q\left[\left(\frac{\partial U_{j,q}}{\partial x_i} + \frac{\partial U_{i,q}}{\partial x_j}\right) - \frac{2}{3}\delta_{i,j}\frac{\partial U_{k,q}}{\partial x_k}\right] \tag{5}$$

The particle momentum equation can be written as:

$$\begin{aligned}\frac{\partial\left(\alpha\rho U_j\right)_p}{\partial t} + \frac{\partial\left(\alpha\rho U_i U_j\right)_p}{\partial x_i} &= -\alpha_p\frac{\partial P}{\partial x_j} + \rho_p g_j + \frac{\partial\Pi_{i,j}}{\partial x_i}\\ &\quad + \beta_j\left(U_{j,q} - U_{j,p}\right) - \frac{\partial}{\partial x_i}\left(\alpha_p\rho_p\overline{U'_{j,p}U'_{i,p}}\right)\\ &\quad - \frac{\partial}{\partial x_i}\left(U_{j,p}\overline{(\alpha_p\rho_p)'U'_{i,p}} + U_{i,p}\overline{(\alpha_p\rho_p)'U'_{j,p}}\right)\end{aligned} \tag{6}$$

The particle temperature equation (also referred to as the $\Theta$ equation) can be written as:

$$\begin{aligned}\frac{3}{2}\left[\frac{\partial}{\partial t}(\alpha\rho\Theta)_p + \frac{\partial}{\partial x_i}(\alpha\rho U_i\Theta)_p\right] &= \Pi_{i,j}\frac{\partial U_{j,p}}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\Gamma_\Theta\frac{\partial\Theta}{\partial x_i}\right]\\ &\quad - \gamma - \frac{3}{2}\alpha_p\rho_p\overline{U'_{i,p}\Theta} - \frac{3}{2}\frac{\partial}{\partial x_i}\left(\Theta\overline{(\alpha_p\rho_p)'U'_{i,p}} + U_{i,p}\overline{(\alpha_p\rho_p)'\Theta'}\right)\end{aligned} \tag{7}$$

In Eqs. (3)–(7) above: $p$ denotes the particle phase; $j$ and $k$ denote the indicator signs of the tensor; $\beta_j$ denotes the drag coefficient component among gas particles along the direction of j; $P$ denotes the pressure, with a unit of Pa; $P_p$ denotes the particle-phase pressure, with a unit of Pa; $\gamma$ denotes the collision energy dissipation; $\Gamma_\Theta$ denotes the temperature transport coefficient of particles; $\xi_p$ denotes the overall viscosity of the particle-phase; and $\mu_p$ denotes the shear viscosity of the particle-phase.