Reduction of dead zones by improving the ventilation system inside the TBM

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ABSTRACT: Ventilation is one of the main components of mechanized tunneling to create a safe working environment for workers and machinery. A three-dimensional numerical model was built to study the airflow behavior and dead zones volume in the tunnel boring machine. Field measurements inside the Chamshir tunnel (Iran) at different cross-sections were also carried out to validate the numerical model. The results show that there are many dead zones from the control cabin to the end of gantry 5 in the backup system. Several applicable scenarios such as setup complete duct and switch off exhausting fan have been studied to minimize the dead zone volume and optimized the airflow velocity. The results show that the dead zones volume can be decreased about 80.09% by setup complete duct from the tunnel portal to the TBM mainframe and switch off the exhausting fan.

KEYWORDS: TBM, Ventilation System, Dead Zone, Safety, Airflow

1. INTRODUCTION

In long tunnels that are excavated by Tunnel Boring Machine (TBMs), there is no natural airflow. Air ventilation should be done artificially in the TBMs. Fresh air has been sent into the TBM via a fan installed in the tunnel portal and through the ventilation duct installed in the tunnel roof. The air in the TBM's at all times must have good quality for breathing and sufficient quantity for diluting or removing gas, dust, and other pollutant level and cooling the air temperature.

In general, the ventilation system in the TBM is performed in three ways: blowing, exhausted and mixed ventilation. In blowing ventilation system, the air is driven by the force fan from the backup system to the mainframe area and in return, the polluted air is transferred out of the TBM. In the exhausting ventilation system, air pollutants are sent to the backup system via an exhaust fan through a galvanized duct from the mainframe. In the mixed ventilation method both force and exhaust fans are used simultaneously. Figure 1 shows a schematic overview of the all ventilation system in the TBMs.

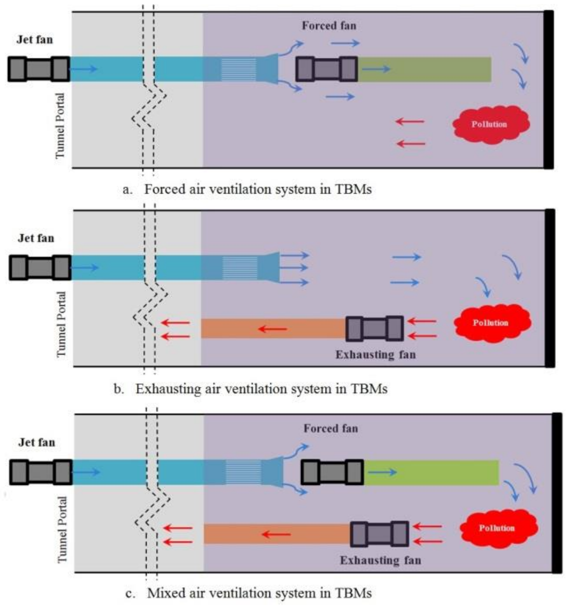


Figure 1 Ventilation System in TBMs

Numerous studies on airflow and gas dispersion in underground mines and tunnels have been reported. Wala et al. studied airflow patterns around the workspace of continuous miners with different boring patterns [1]. Aminossadati and Hooman. modeled a 2D model in order to evaluate the effect of brattice length on the airflow velocity [2]. Zheng and Tien. used Fluent and Gambit to evaluate airflow pattern and DPM concentration in underground mines [3]. Taylor et al. investigated the impact of the setback distance on airflow and methane distribution [4]. Diego et al. calculated air losses in circular tunnels by both traditional and CFD methods [5]. To investigate airflow behavior and methane distribution in the room and pillar underground coal mine, a computational study was carried out [6]. Xu et al. used trace gas technology and CFD to simulate airflow inside the mines [7].

Many studies have tried to improve the efficiency of dust and DPM control. Qiao et al. monitored the concentration of Particulate Matter (PM) in a subway tunnel [8]. Similarly,Torano et al. used CFD to predict airflow and dust dispersion in a mechanized underground coal mine [9]. In another study, Kurnia et al. validated the three-dimensional CFD model utilizing Eulerian-Lagrangian approach to track the dispersion of dust particle [10]. Hu et al. studied coal dust particle behavior after blasting in a roadway [11]. Thiruvengadam et al. simulated DPM by CFD and compared between the particle and species model [12]. Xia et al. used CFD to stimulate dust suppression for open type TBM [13]. Zheng et al. revealed the effect of single dead-end entry inclination on DPM plume dispersion by CFD methods [14]. Yueze et al. Predicted methane gas and coal dust dispersion in room and pillar mining face [15].

In summary, the numerical study of airflow has mainly concentrated on underground mines and road tunnels. Ventilation during the construction of long tunnels, especially the ventilation of TBMs, has received less attention. Previous work in our group [16] showed that mixed ventilation system has not minimum airflow velocity in 59.6% of TBM space. Increasing airflow rate of the forced fan shows dead zone volume can be decreased about 5.21%. To extend the work on optimization airflow pattern and minimizing dead zones in TBMs, the aim of the work presented is threefold: (i) to examine the effect of switch off exhausting fan (Blowing ventilation system) on dead zones volume; (ii) to evaluate the effectiveness of complete duct from tunnel portal to the TBM mainframe configuration; (iii) to investigate the effect of setting up complete duct from tunnel portal to the TBM mainframe and switching off exhaust fan simultaneously with respect to the dead zones.

2. MODELING

2.1 Physics of the problem

The whole space of the TBM in Chamshir tunnel is considered as the modeling area. Chamshir water transport tunnel is located in South of Iran. This tunnel, which is being constructed using single-shield TBM, will have a final diameter of 4.6 m. Three ventilation systems have been applied in this tunnel to provide adequate air quality during normal operation. Three axial type forced fans have been connected serially in the portal of Chamshir tunnel to send fresh air with flexible ducting from tunnel portal to the end of the backup system in 1400 m length. In order to deliver fresh air to the TBM mainframe area, a blowing fan (55 kW) with hot dip galvanized duct has been installed in gantry 2. The wye tee (pant) divides the airflow duct between two parallel legs as inlet 1 and 2. Setback distance or the distance of the ventilation duct from the shield space in inlet 1 and 2 is 16 and 19 m respectively (Figure 2). Exhausting fan with 15 kW power in gantry 4 sucks pollutants produced by the locomotive and sends it to the end of the backup system.

Due to the geometric complexities of the problem, simplifications were made in the machine geometry according to Figure 3. This TBM geometry is taken from the previous work [16].

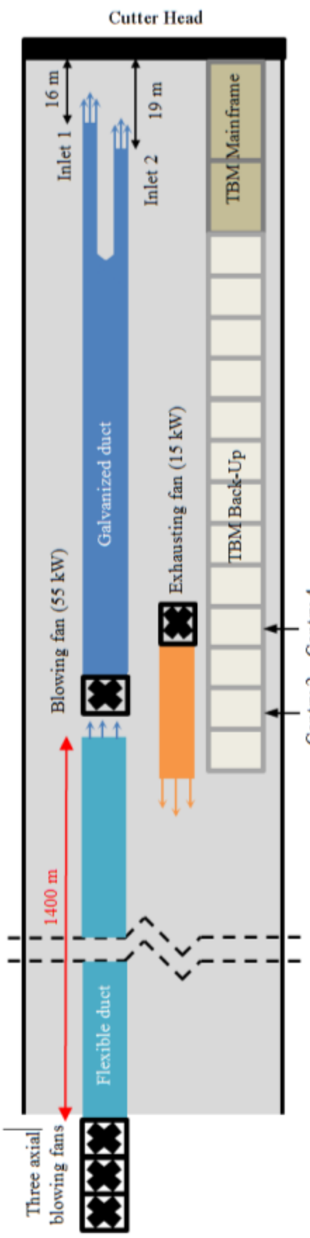


Figure 2 Ventilation Systems in Chamshir TBM

Figure 3 Computational TBM geometry model

2.2 Governing equations

The airflow in the whole workspace of the studied TBM could be solved by Reynolds-Averaged Navier-Stokes (RANS) equations. The most commonly used turbulence model in engineering, standard K–ε, is selected in this work based on validation with experimental flow measurement in our previous work [16]; for the sake of brevity, the validation is not repeated here. The governing equations are integrated over each control volume. The equations are as follows:

Continuity equation:

$$\partial \rho / \partial t + \nabla . (\rho U) = 0 \quad (1)$$

Momentum equation:

$$\partial / \partial t \ (\rho U) + \nabla . (\rho U U) = -\nabla P + \nabla . \tau + S_M \quad (2)$$

Energy equation:

$$(\partial(\rho h_{tot}))/ \partial t - \partial p / \partial t + \nabla . (\rho U h_{tot}) = \nabla . (\lambda \nabla T) + \nabla . (U . \tau) + U . S_M + S_E \quad (3)$$

Turbulent kinetic energy equation:

$$\partial / \partial t \ (\rho k) + \nabla . (\rho k U) = \nabla . [(\mu + \mu_t / \sigma_k) \nabla k] + P_k - \rho \varepsilon \quad (4)$$

Turbulent dissipation rate equation:

$$\partial / \partial t \ (\rho \varepsilon) + \nabla . (\rho \varepsilon U) = \nabla . [(\mu + \mu_t / \sigma_\varepsilon) \nabla \varepsilon] + \varepsilon / k (C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon) \quad (5)$$

In above equations, ρ is the air density, $\vec{U} = (v_x, v_y, v_z)$ is the air velocity vector, $\overrightarrow{\nabla P}$ is the pressure gradient, τ is the stress tensor, $S_M = (S_{Mx}, S_{My}, S_{Mz})$ is the vector of momentum source, h_{tot} is the total enthalpy, $\nabla.(U.\tau)$ represents the work due to viscous stresses, $U.S_M$ represents external momentum source, S_E is the energy source, k is turbulence kinetic energy, λ is the Lam´es coefficient, ε turbulence eddy dissipation, respectively and P_k is turbulence production. The default values for the turbulence model constants are $C_{\varepsilon 1} = 1.44$ and $C_{\varepsilon 2} = 1.92$ [17].

2.3 Boundary conditions

The applicable boundary conditions are shown in table 1. The standard wall function is used in all simulation. The outlet 1 boundary condition was set to the atmospheric pressure.

Table 1 Boundary conditions

Scenario	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Outlet 2	Outlet 3
Benchmark	7.90	5.62	18.00	10.04	2.73	7.70
Switch off exhaust fan	7.90	5.62	0	10.04	2.73	0
Setting up complete duct	29.28	20.78	18.00	0	0	7.70
Setting up complete duct & switch off exhausting fan	29.28	20.78	0	0	0	0

2.4 Mesh generation in the computational domain

The computational domains were created, meshed and labelled in ANSYS ICEM CFD. Similar to the previous study, five different number of grids, i.e. 27×10^6, 36×10^6, 49×10^6, 52×10^6 and 57×10^6, were implemented and compared for the average velocity at steady monitor point to ensure a mesh independent solution.

2.5 Solution strategy

To complete the discretization of the advection term, the high-resolution scheme was computed [16]. Root Means Square (RMS) < 10^{-4} was considered as the convergence criterion of mass and momentum equations. A computer with 24 processors and 60 GB RAM was used for convergence purposes, where 3000 iterations were calculated in about 98 hours. To evaluate convergence, mass and momentum imbalance were considered below 1% in different directions. In addition, air velocity was monitored until it no longer changed with more iteration. When convergence was assured, the curve of the variations of air velocity in the lateral sections of the studied TBM was developed in order to assess airflow distribution.

3. Results and discussion

In the previous work, we modeled the TBM ventilation system using the CFD method to obtain an understanding of airflow behavior in a TBM. It was found that the mixed ventilation system model as benchmark could not remove the dead zones inside the TBM. Results show that dead zones are present in sections 1 to 7 in crew pathways and staying places. Accordingly, dead zones are 59.6% of the TBM in volume and as such airflow is not satisfactory for the ventilation of the TBM.

3.1 Switch off exhausting fan

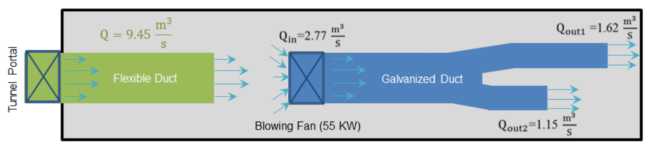
The exhausting fan was employed in gantry 4 to remove locomotive exhaust pollutants. In the presence of exhausting fan (i.e., Switch OFF), the volume of the dead zones in TBM is calculated as 1249.44 m^3 . Fig 4 shows dead zones volume in switch off exhausting fan scenario. Accordingly, switching off the exhaust fan leads to a decrease in the dead zones about 1.51%. In Fig 8-a, dead zones in longitudinal crew pathway section are shown. Although switching on the exhaust fan can help to reduce concentration of the locomotive pollutant, it has a reverse effect in dead zone areas. This scenario recommends that the exhausting fan be switched off when the locomotive is out of the TBM.

Figure 4 Dead zone volume in switch off exhausting fan scenario

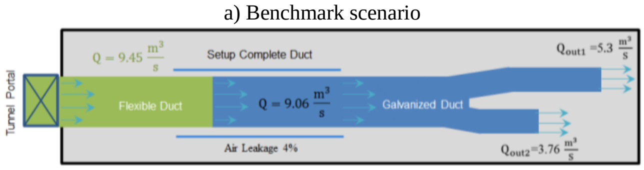
3.2 Setting up complete duct from tunnel portal to the TBM mainframe

In the benchmark scenario, the airflow rate in the flexible duct at the end of the backup system (inlet 4 mass flow rate) was 9.45 m3/s. The total flow rate of air directed to the mainframe area by the blowing fan (inlet 1 and 2) was 2.77 m3/s. this means that the mass flow about 6.68 m3/s is flow at the end of the backup system in gantry 2 (See Fig 5- a). It has been shown that the benchmark scenario is not adequate in driving sufficient airflow and removing the dead-zone area.

In this scenario, setting up complete duct, from the tunnel portal to the mainframe area, was studied. Fig 5-b presents a visual presentation of the mass flow data. Air mass delivered to the end of the galvanized duct via a complete ducting system was calculated by Gillies and Wu (1999) and air leakage was estimated to be about 4% [18]. This approach can be implemented by installing a complete duct from the tunnel portal to the mainframe area to direct fresh air toward the mainframe area. Dead zone volumes in setting up complete duct from tunnel portal to the TBM mainframe scenario is shown in Fig 6.



a) Benchmark scenario



b) Setting up complete duct scenario

Figure 5 Boundary condition in benchmark and setup complete duct scenarios

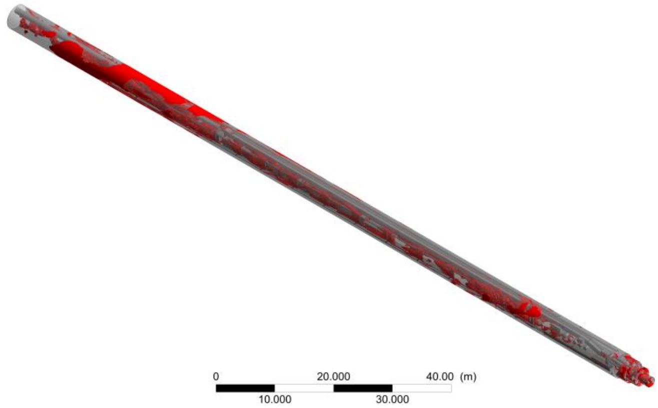


Figure 6 Dead zone volumes in setting up complete duct from tunnel portal to the TBM mainframe scenario

The results, as illustrated in Table 2, indicate that dead zones volume in this scenario was decreased about 62.92%. The colour contour in Fig 8-b represents the dead zone in longitudinal crew pathway section with the air velocity level below the regulation limit of 0.3 m/s.

3.3 Setting up complete duct from tunnel portal to the TBM mainframe and switch off exhausting fan

The setup complete duct and the numerical study were mentioned in the previous paragraph. This system is similar to previous scenario, where the exhaust fans has been switch off. The modeling results show that the use of complete duct and switch off exhausting fan decreases dead zones volume 80.09% (Fig 7). Compared with Fig 8-c, there was a large improvement in the ventilation of crew pathway and staying place.

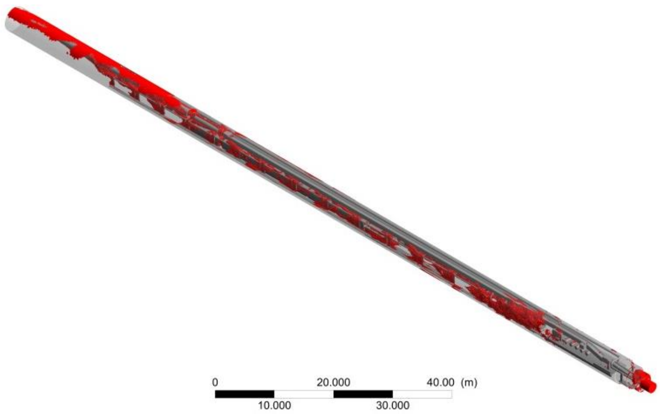


Figure 7 Dead zone volumes in setting up complete duct from tunnel portal to the TBM mainframe and switch off exhausting fan scenario

Table 2 Dead zone volume in scenarios

Scenario	Dead zone volume (m^3)	Dead zone decreasing ratio (%)
Benchmark	1268.59	-
Switch off exhausting fan	1249.44	-1.51
Setting up complete duct	470.33	-62.92
Setting up complete duct & switch off exhausting fan	252.56	-80.09

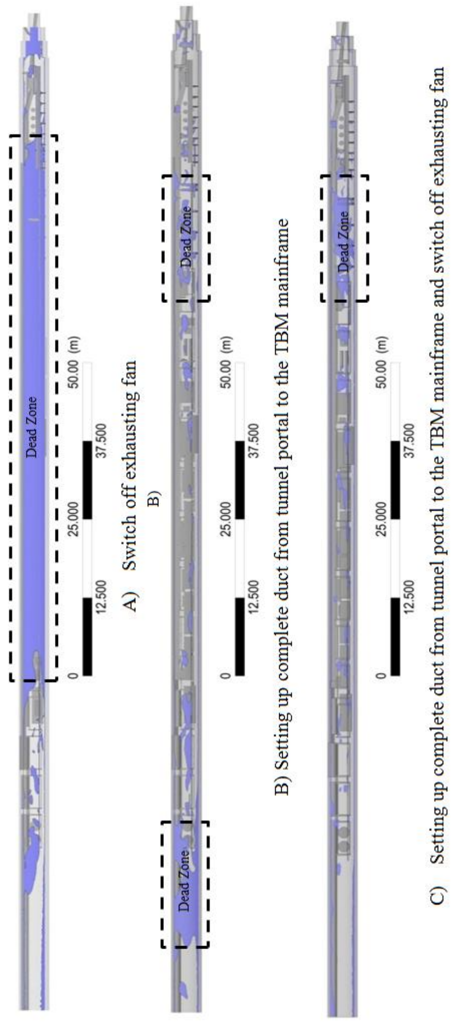


Figure 8 Dead zones in longitudinal crew pathway section

3. CONCLUSION

To optimize ventilation system and air flow pattern inside single shield TBM was numerically simulated using the CFD approach. Dead zone volume in benchmark was about 59.6% of the total space of the machine. Several relevant scenarios were studied to decrease the number of dead zones and optimize relative airflow velocity. It was shown that using complete duct and switch off exhausting fan in the ventilation system is effective and significant in decreasing dead zone in TBM. It is particularly important to switch off the exhausting fan when the locomotive is not working in the backup system.

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