

Spatial-Temporal Analysis of Lung-Deposited Surface Area (LDSA) concentrations, related to Diesel Particulate Matter (DPM) in Underground Mines

by

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ORIGINALITY STATEMENT

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ABSTRACT

Diesel particulate matter (DPM) presents a significant occupational health risk in underground mining environments due to confined geometries, continuous diesel emissions, and complex ventilation-induced airflow patterns. Conventional exposure assessment methods rely on mass-based, time-weighted averages, which do not adequately capture spatial variability or represent the biologically relevant dose associated with particle deposition in the respiratory system. This study investigates the spatial distribution of DPM within a mechanically ventilated underground mine drift and examines the relationship between particle mass fraction and lung-deposited surface area (LDSA) as a health-relevant exposure metric. A computational fluid dynamics (CFD) model was developed to simulate airflow, pollutant transport and assess hazard mapping, with DPM represented as a passive scalar and subsequently converted into BC concentration and LDSA. The results reveal pronounced spatial heterogeneity in pollutant distribution, governed by ventilation-induced flow structures. Recirculation zones near the emission source were identified as regions of elevated concentration and increased exposure risk, while ventilation reduced pollutant levels non-uniformly along the drift. A non-linear reduction in concentration was observed, with limited dilution near the source and more effective transport further downstream. The findings demonstrate that exposure risk in underground mines is highly location-dependent and influenced by both airflow dynamics and vertical position.

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1. INTRODUCTION

The conditions of underground mining pose a complicated occupational exposure to underground mining because of the geometries that are confined, the ventilation that is mechanically driven, and the constant presence of diesel-powered equipment. These factors encourage the build-up and disproportionate distribution of air pollutants, especially diesel particulate matter (DPM), which is still one of the most critical air quality issues in underground mines (Liu et al., 2024).

The existing regulatory and monitoring strategies of diesel particulate matter (DPM) exposure in underground mines are mainly founded on mass-based indicators, including elemental carbon (EC) and total carbon (TC), which are usually presented in terms of time-weighted average concentrations (Khan et al.; Salo et al.). Although these measures are appropriate in regulatory compliance, they fail to provide a reasonable measure of health-relevant exposure. Specifically, mass-based measurements fail to consider size-dependent behavior and deposition of particles in the respiratory system, which are key factors of biological impact (Oberdorster et al.). Moreover, these methods are based on time-averaged and single-point measurements, which may mask considerable spatial differences in pollutant concentrations. The airflow patterns induced by ventilation and local recirculation areas in underground mines may lead to extremely heterogeneous distributions of pollutants, which lead to exposure conditions that cannot be measured by standard monitoring techniques (Salo et al.).

As a way of overcoming these shortcomings, other exposure indicators have been considered. Black carbon (BC) has been well-known as a stable indicator of diesel emissions and has the benefit of real-time measurement, which can be used to assess the distribution of pollutants in detail (Janssen et al.; Sabanov et al.). Simultaneously, a health-relevant measure, lung-deposited surface area (LDSA), has also been suggested, since it is the surface area of particles that deposit in the respiratory tract. In contrast to mass-based metrics, LDSA offers a more direct connection to possible biological impacts and has been demonstrated to be associated with poor health outcomes (Oberdörster et al.; Schmid & Stoeger).

Past research has shown that there is a close correlation between BC and LDSA in outdoor conditions like urban traffic and harbour conditions (Lepistö et al.; Kuula et al.). Nevertheless, the results cannot be directly transferred to underground mines where the airflow behavior and the transportation of pollutants are controlled by other mechanisms. Underground drifts Ventilation systems create high-velocity jets which interact with the tunnel boundaries, creating flow features, including impingement, recirculation, and backflow (Salo et al.). These flow structures produce very non-uniform distributions of pollutants and can have a large impact on the patterns of exposure. Consequently, the correlation between BC and LDSA in such circumstances is unclear and needs to be explored.

To fill this gap, this paper examines the spatial distribution of diesel particulate matter in a mechanically ventilated underground mine drift and its correlation with black carbon and the surface area that is deposited on the lungs. A computational fluid dynamics (CFD) model is used to simulate airflow and transport of pollutants in a simplified yet representative mine geometry. In this model, diesel PM is modelled as a passive scalar mass fraction variable ('hv_vol'), which is the ratio of pollutant mass to the air-particle mixture. The convection and turbulent diffusion control the evolution of this scalar field, which characterizes the transport of airflow and dispersion through mixing. The pollutant is assumed to be a passive scalar, i.e. it does not affect the airflow, and the processes of deposition, agglomeration and chemical transformation are not taken into account.

The resultant mass fraction field gives a dimensionless expression of the distribution of pollutants that is then converted to the equivalent black carbon concentration ($\mu\text{g}/\text{m}^3$) using air density. This enables the results of the simulation to be interpreted as quantifiable exposure amounts. Besides, lung-deposited surface area (LDSA) is estimated based on the concentration of BC using an empirical relationship that is reported in the literature. This transformation allows connecting the distribution of pollutants calculated by CFD with a health-relevant exposure measure. It should be mentioned that LDSA is not directly modeled but is obtained by deriving BC and thus, the correlation between these variables in this research is not grounded on empirical validation but assumed empirical model.

Problem statement:

The assessment of diesel particulate matter (DPM) exposure in underground mines remains largely based on mass concentration metrics, which do not adequately represent the health-relevant dose experienced by workers. In particular, lung-deposited surface area (LDSA) has not been sufficiently analyzed in relation to DPM exposure and its implications for risk assessment in underground mining environments. This gap is especially critical at the human respiratory level (1.5–1.9 m), where miners are directly exposed and where airflow patterns and pollutant accumulation can vary significantly. The lack of spatially resolved LDSA analysis limits the ability to accurately evaluate exposure risk and identify high-risk zones within mine drifts. Understanding the spatial distribution of LDSA is therefore essential for hazard mapping and for identifying areas of elevated exposure. The aim of this study is to analyze the spatial dynamics of LDSA concentrations related to diesel particulate matter exposure in an underground mine drift.

The main objectives of this study are as follows:

1. To review existing literature on particulate matter exposure and identify limitations in current assessment approaches.
2. To propose a suitable methodology for analyzing the spatial distribution of particulate matter and its health-relevant exposure metrics.
3. To construct a computational fluid dynamics (CFD) model to simulate airflow and pollutant transport, including air velocity and mass fraction distribution, within an underground mine drift.
4. To analyze the simulation results and correlate pollutant mass fraction and lung-deposited surface area (LDSA).
5. To identify and propose hazard mapping zones based on spatial variations in exposure levels within the mine drift.

This study, by integrating CFD-based airflow and pollutant transport modelling with the interpretation of health-relevant exposure measures, offers a framework for understanding the effect of ventilation structures on the distribution of pollutants and the potential respiratory exposure. The results are useful in enhancing the assessment of exposure in underground mines by emphasizing the role of spatial variability and in the development of more representative methods of monitoring.

2. LITERATURE REVIEW

2.1 Diesel Particulate Matter in Underground Mines

Diesel particulate matter (DPM) is a complicated aerosol blend that is produced due to incomplete combustion in diesel engines. Elemental carbon (EC) is the main constituent and it develops a fractal agglomerate structure and has a high surface area. EC is a significant fraction of total carbon (TC) and TC is a large fraction of total DPM mass in underground mine settings (Khan et al.; Kimbal et al.). The rest of the fraction is organic compounds, sulphates and metallic elements that are adsorbed onto the EC core.

Diesel exhaust composition depends on engine operating conditions, fuel properties and the use of emission control technologies like diesel particulate filters. Nevertheless, EC is a good tracer of diesel particulate emissions in underground metal and non-metal mines where other sources of carbon are mostly absent (Khan et al.; Ristovski et al.). This carbonaceous pre-eminence forms the basis of using carbon fractions as surrogate measures of DPM in occupational exposure assessment.

It has been shown that there is strong empirical correlation between EC, TC, and total DPM mass in underground mining conditions, which can be used in regulatory frameworks (Khan et al.). Nevertheless, the introduction of emission control technologies can influence such relationships as they can change the composition and behavior of diesel particulate emissions (Kimbal et al.). Physical properties of DPM determine its transportation and deposition in respiratory system. The size range of diesel particles is mostly in the submicrometer range, which allows the particles to penetrate deep into the respiratory tract and settle in the areas with limited clearance (Salo et al.). This behavior has significant consequences to exposure assessment, because it demonstrates the shortcomings of measures based purely on particle mass.

The important point of observation that is highlighted by Salo et al. is that the current exposure limits that are based on mass do not sufficiently consider ultrafine particles, which are particles less than 100 nm in diameter. These particles have the ability to enter deep into the human respiratory system and settle in the pulmonary alveoli, where the clearance processes are the least

effective, and biological interaction is the most important (Salo et al.). This is especially significant since most of the diesel particle emissions, when considered in terms of number concentration, but not mass, lie in this ultrafine size range (Salo et al.). Consequently, mass-based measurements, which are over-representative of larger particles, systematically underestimate the proportion of the most biologically active fraction of particulate matter.

Engine operating conditions also affect the characteristics of diesel particulate matter. Barrett et al. showed that the emissions of particles differ greatly when the diesel engines are operated at low and high loads, which represent the spectrum of conditions experienced in the underground mines. These differences influence the rate of emissions and the properties of the particles, which leads to the variability of the exposure conditions across the mine.

DPM exposure regulatory frameworks are heavily founded on carbon-based measures based on these mass-based measures. In the United States, the Mine Safety and Health Administration (MSHA) set a permissible exposure limit (PEL) of total carbon in underground mines, as it was observed that carbon is about 70-90 percent of the total DPM mass (Khan et al.). Likewise, the elemental carbon limits are suggested to be $100 \mu\text{g}/\text{m}^3$ by international standards, including those in Finland and Switzerland, which is characteristic of diesel emissions (Salo et al.). These methods offer a standardized and practical foundation of exposure assessment. Nonetheless, these regulatory procedures are based on whole-shift integrated sampling, which yields time-weighted average concentrations that fail to reflect short-term changes and spatial variability in the mine environment. The airflow structures, equipment movement, and localized recirculation zones in mechanically ventilated underground drifts may cause a large difference in the concentration of pollutants in space and time. Therefore, mass-based measurements, on average, can mask localized areas of high exposure.

This lack of correspondence between measured mass concentration and biologically relevant exposure is one of the basic shortcomings of existing occupational hygiene practices. Although mass-based measures are still valuable in regulatory contexts, they do not sufficiently reflect the particle properties that define deposition and health effect. This drawback directly warrants the exploration of other exposure measures that are more reflective of the biologically relevant dose. Surface area of particles depositing in the respiratory tract has become an attractive

measure in this regard, with lung-deposited surface area (LDSA) being a promising measure. LDSA offers a more direct connection to potential health effects than mass concentration alone by including the behavior and deposition properties of particles. The connection between real-time measurements of black carbon and LDSA, especially in the context of spatially variable conditions of underground mines, is thus critical to the next stage of exposure assessment, beyond the constraints of traditional methods. This is the main driving force of the current research.

2.2 Black Carbon as a Real-Time Tracer for Diesel Particulate Matter

Black carbon (BC) is one of the main aerosol pollutants formed during the incomplete burning of carbon-containing fuels and is commonly known to be a major constituent of diesel PM. Diesel engines are the primary source of BC in underground mining conditions, which is why it is a good measure of diesel emissions (Sabanov et al.). BC has good light-absorbing capacity and stability, which allows its effective measurement by optical methods, thus real-time monitoring of pollutant concentrations.

The language of BC needs to be made clearer, because it is frequently confused with other similar terms, like soot or elemental carbon. Although these terms denote similar carbonaceous materials, they are different in the way they are measured. Thermo-optical analysis determines elemental carbon (EC), and operationally defines BC in terms of its light-absorbing properties (Sabanov et al.; Janssen et al., 2012). Although this is different, BC and EC are highly correlated in diesel-dominated environments. This high correlation is the basis of using BC as a proxy of diesel particulate matter. Research has shown that BC levels are highly responsive to changes in DPM and total carbon levels, especially in those environments where the major source of carbonaceous particles is diesel emissions (Choi et al.; Sabanov et al.). In contrast to organic carbon and other constituents of particulate matter, BC is directly linked to the process of combustion and is highly specific to diesel emissions in underground mines. Consequently, BC offers an efficient and convenient way of real-time monitoring of diesel particulate matter. This is especially essential in underground mine conditions where the levels of pollutants may differ greatly based on the ventilation patterns, equipment use, and the physical location. The capability to measure these variations renders BC a useful instrument in measuring exposure beyond the constraints of time-integrated, mass-based measurements.

The concentration of black carbon (BC) is measured indirectly by optical techniques with aethalometers, which measure the attenuation of light in an aerosol sample and convert this attenuation to mass concentration with a mass absorption cross-section (MAC) value. This technique allows the real-time and continuous measurement of BC, and thus, short-term changes in the concentration of a pollutant that is impossible to measure with other traditional integrated sampling methods can be detected.

A major weakness of this method is the uncertainty that the MAC value has. MAC is not a constant and thus cannot be regarded as a universal parameter, which adds systematic error to the determination of the mass concentration of BC (Zhang et al.; Bond et al.). This problem is especially topical in the conditions of underground mines where newly released diesel aerosols can have optical characteristics that are not similar to old ambient aerosols to which numerous correction algorithms have been designed (Sabanov et al.). Consequently, when interpreting BC data in these circumstances, attention to measurement uncertainty is needed. Conversely, compliance-based DPM monitoring is based on thermal-optical analysis of samples of filters taken at full work shifts. Although this approach offers standardized mass-based measurements, it yields time-integrated values that fail to capture short-term variability, and do not give any information on spatial differences in pollutant concentration within the mine (Barrett et al.). This is especially important in conditions where the distribution of pollutants is highly non-uniform due to airflow patterns and sources of emissions.

The main benefit of BC monitoring compared to traditional EC filter sampling is that it can give real-time information. The patterns of pollutant concentration that occur in underground mining settings due to diesel equipment movement, ventilation dynamics, and operational cycles are short-periodic. Integrated sampling techniques that average these changes across a whole work shift can hide both the maximum exposures and the locations and activities that cause high concentrations. Conversely, real-time BC monitoring makes it possible to continuously monitor these changes and identify high-exposure conditions better and evaluate ventilation performance more effectively (Sabanov et al.).

Specificity of the source is another benefit in underground mines. Diesel engines are the leading source of submicrometer light-absorbing carbon in both metal and non-metal mines. BC

is a more selective indicator of diesel emissions as opposed to organic carbon, which can be generated by various sources (Noll et al.). This particularity is especially useful in complicated mine atmospheres, when mineral dust, blasting emissions, and other sources of particulate matter are present.

The close empirical correlation between BC and diesel PM also justifies its use as a surrogate exposure measure. It has been demonstrated that elemental carbon (EC) is highly correlated with total carbon and DPM mass in underground mining setting, especially without diesel particulate filter systems (Khan et al.). Since BC is highly correlated with EC in diesel-dominated aerosols, optically measured BC can be used to give a continuous signal that is sensitive to changes in DPM concentration (Sabanov et al.; Choi et al.).

Collectively, these properties render BC a useful and efficient instrument to comprehend the spatial and operational variability of diesel particulate matter in underground mines. This is especially useful in estimating localized exposure regions, and the effect of ventilation-driven airflow on the distribution of pollutants, which is not possible with traditional time-integrated measurement methods. Although real-time BC monitoring has its benefits, there are a number of significant limitations that should be taken into account. The results of different analytical methods applied to determine the concentration of BC can vary significantly, especially when old or internally mixed particles are present (Zhang et al.). These inconsistencies are due to the variation in the principles of measurement and the operational character of BC as a measure.

There are certain sources of uncertainty in aethalometer-based measurements. The multiple scattering in the filter medium and the shadowing effect of the particle accumulation on the filter surface can influence light attenuation measurements. These effects necessitate the use of correction factors, which add more uncertainty, especially at high concentrations (Sabanov et al.). The largest source of uncertainty is related to the mass absorption cross-section (MAC). MAC is not a constant since it depends on the particle size, morphology, and chemical composition. Consequently, there is systematic error in the conversion of the light attenuation to the BC mass concentration (Zhang et al.; Bond et al.). This constraint is especially applicable in the underground mine settings, where new aerosols of diesel can vary significantly compared to the old ambient aerosols that are used to obtain standard MAC values (Sabanov et al.).

These uncertainties highlight the need for careful interpretation of BC measurements in mine-specific conditions. Nevertheless, they do not compromise the usefulness of BC as a real-time measure of diesel particulate matter. Instead, they focus on the need of validation in the use of BC measurements in quantitative exposure assessment, especially in the context of associating the BC concentration with health-relevant exposure measures like the lung-deposited surface area.

2.3 Lung-Deposited Surface Area as a Health-Relevant Exposure Metric

Lung-deposited surface area (LDSA) is a measure of the total surface area of airborne particles depositing in the human respiratory tract, per unit volume of air. In contrast to traditional measures of particulate matter, like $PM_{2.5}$ or PM_{10} , which describe exposure in terms of particle mass, LDSA takes into account the size distribution of particles and the likelihood of deposition in various parts of the lung (Mukherjee et al.; Lepisto et al.). Consequently, it gives an estimate that is closer to the biologically relevant dose that is administered to lung tissue.

The applicability of LDSA is founded on the interrelation of particle size and deposition characteristics in the respiratory system. Smaller particles have a higher probability of getting deeper into the lungs, especially into the alveolar area, where gas exchange takes place and clearance processes are minimal (Mukherjee et al.). This renders deposition in this area especially significant in determining the possible health impacts. LDSA explains this behavior by contributing the weight of the particles to the deposition, but not their mass. The estimation of LDSA may be made through the combination of particle size distribution and deposition models, including those proposed by the International Commission on Radiological Protection (ICRP, 1994), that characterize the deposition efficiency of particles of different sizes in the respiratory tract. This method allows the transfer of particle properties to a scale that indicates possible biological interaction.

Compared to the mass-based measures, LDSA offers a more significant expression of exposure in the environment where fine and ultrafine particles are prevalent, e.g., diesel particulate matter. It provides a better foundation on which exposure can be assessed in underground mine settings by considering the behavior of particles in the respiratory system and therefore the traditional measures may not be sufficient to measure the features that determine health risk. The

basic reason why LDSA is a health-relevant measure of exposure is based on the mechanism by which inhaled particles interact with biological systems. The cellular-level toxicity of particles is determined by the surface interactions of insoluble particles with respiratory tract membranes, but not the mass of deposited material (Oberdorster et al., 2005; Schmid and Stoeger, 2016). The higher the surface area of the particles, the more sites of chemical and physical interaction, and the higher the possibility of oxidative stress, inflammatory reactions, and the resultant cellular damage.

This process is especially applicable to the case of diesel particulate matter. The diesel particles have an elemental carbon (EC) core that is insoluble and refractory, which enables the particles to remain in the lung environment and continue to have a long-term contact with the alveolar tissue. Moreover, small primary particle size and fractal-like morphology of diesel emissions leads to high surface-area-to-mass ratio. As a result, the relatively low mass concentrations of diesel particles may be associated with a significant reactive surface area in the respiratory system (Lepisto et al.).

This mechanistic understanding is backed by empirical evidence. It has been experimentally demonstrated that the surface area of particles is a better predictor of acute inflammation of the lungs compared to particle mass or number concentration (Schmid and Stoeger, 2016). Likewise, epidemiological analyses have revealed that LDSA is more strongly associated with poor health outcomes, such as decreased lung function, subclinical atherosclerosis, and higher mortality rates, than traditional mass-based measures, such as $PM_{2.5}$ or PM_{10} (Patel et al., 2018; Aguilera et al., 2016; Hennig et al. Other researchers have also established that particle surface area concentration is more correlated with the negative health effects compared to mass or number concentration (Brown et al., 2001; Oberdorster et al., 2005).

Collectively, these results make LDSA a more biologically relevant measure of exposure compared to conventional mass-based measures. This is especially significant in conditions where there is a preponderance of diesel emissions where particle properties are conducive to high surface reactivity. Consequently, LDSA offers a better foundation on which exposure in underground mine settings can be evaluated and can be used alongside real-time measures like black carbon to further characterize the exposure.

One of the most important findings of the ambient air quality studies is that the concentration of the lung-deposited surface area (LDSA) is expected to be the highest at the particle sizes of approximately 100 nm (Kuula et al., 2020; Kuuluvainen et al., 2016). This size range is very similar to the normal size distribution of the black carbon (BC) particles, which are usually located in the soot mode of about 30 to 300 nm (Kumar et al., 2010). This coincidence is not accidental; it is a manifestation of the fact that BC particles are within the size range that is best deposited in the alveolar area of the respiratory system and thus is a major contributor to LDSA. Due to this correspondence, there have been strong correlations between equivalent black carbon (eBC) and LDSA in various environments. The results of studies in traffic-affected locations, harbour environments, and residential combustion indicate the presence of significant correlations between BC concentration and LDSA (Hama et al., 2017; Cheristanidis et al., 2020; Kuula et al., 2020). These results indicate that BC, which may be continuously measured with aethalometers, can be used as a convenient substitute of LDSA, which is usually measured with more sophisticated equipment.

In addition to this size-related association, BC can also affect health risk by its capacity to transport toxic substances. BC is a highly surface reactive substance, which can adsorb polycyclic aromatic hydrocarbons, transition metals, and other pollutants related to combustion. These compounds may be carried to the deepest parts of the alveolar region together with BC particles, where the systemic absorption is most effective. This is known as the Trojan horse effect and increases the possible health effect of BC by increasing the surface area exposure and delivery of toxic co-pollutants (Ortega et al., 2014).

Combined, these results suggest that BC is not merely a marker of diesel emissions, but also strongly associated with the health-relevant particle fraction that is LDSA. This association gives the rationale to use BC as a surrogate measure of biologically relevant exposure. Most of the available literature has however been done under ambient conditions and it is still unclear how this relationship can be applied in the limited and ventilation-driven conditions of underground mines. This weakness underscores the importance of additional research in these settings. Although there is a solid scientific rationale in support of lung-deposited surface area (LDSA) as a health-relevant exposure measure, it is still not regulated in occupational and environmental settings. In contrast to the traditional measurements, like $PM_{2.5}$ and PM_{10} , where the World Health Organization offers

guidance values, there are no such standards available to LDSA at the moment (WHO, 2021). This regulatory gap is indicative of two important issues: the absence of generally accepted measurement protocols and the paucity of studies that directly relate LDSA to particular toxicological and epidemiological outcomes in the workplace (Liu et al., 2023).

This is a significant gap in underground mining conditions. Despite the fact that the association between black carbon (BC) and LDSA has been determined in the ambient conditions like urban traffic and harbour conditions, the results cannot be directly applied to underground mines. The nature of mine environments varies radically because of their constrained geometry, the closeness and strength of diesel emission sources, and the existence of mechanically driven ventilation systems that produce complicated airflow structures. The conditions lead to spatially heterogeneous distributions of pollutants that cannot be modeled in open atmospheric conditions.

Furthermore, underground mines are typified by a high level of pollutants and the presence of several sources of particulate matter, such as diesel emissions, mineral dust, and aerosols of blasting. These can affect the behavior of particles and the properties of measurements, which can affect the correlation between BC and LDSA. Consequently, it is not clear how applicable BC is as a proxy of LDSA in such circumstances.

This uncertainty is a critical issue that needs to be addressed in order to develop exposure assessment in underground mining. Specifically, it is important to assess the spatial distribution of BC and LDSA in a ventilated mine drift to understand the possibility of real-time BC monitoring as a predictor of health-relevant exposure. The need is the foundation of the current research, which examines the spatial correlation between BC and LDSA under controlled ventilation conditions.

2.4 The Relationship between Black Carbon and Lung-Deposited Surface Area

The correlation between black carbon (BC) and lung-deposited surface area (LDSA) is explained by the fact that the size distribution of the BC particles is aligned with the particle sizes that are most efficient in depositing in the alveolar part of the human lung. In urban ambient air, the LDSA concentrations are usually at the highest level at the particle diameter of approximately 100 nm (Fierz et al., 2011; Reche et al., 2015; Kuuluvainen et al., 2016). This size range is very

similar to the soot mode of BC particles, which typically has a range of about 30 to 300 nm (Lepistö et al., citing Kumar et al., 2010).

Since the particles in this size range are best deposited in the alveolar region by diffusion mechanisms as outlined by the International Commission on Radiological Protection (ICRP, 1994), BC particles are important contributors to LDSA. This overlap offers a good physical foundation to anticipate that BC concentration will be associated with the surface area of the particles that settle in the lungs. The physical properties of BC particles also support this relationship. BC consists of insoluble, recalcitrant material which remains in the lung environment and has long-term contact with respiratory tissues. Moreover, the BC particles have a fractal agglomerate structure which is composed of small primary carbon spherules and this leads to a high surface-area-to-mass ratio relative to more compact sized particles of the same size (Bond et al., 2013).

The product of effective alveolar deposition, retention in the respiratory tract, and large reactive surface area renders BC especially effective in delivering the type of particle surface LDSA is designed to measure. Consequently, the concentration of BC can be used as a physically significant measure of the surface area deposited in the lung in relation to combustion-generated aerosols.

The hypothesis that black carbon (BC) can be used as a useful proxy of health-relevant exposure has been proven by empirical evidence of the relationship between black carbon (BC) and the lung-deposited surface area (LDSA) over a variety of environments. A systematic study of this relationship in the street canyon, highway and harbour settings in the Helsinki metropolitan area by Lepistö et al. (2022) found a consistently high level of correlation between BC and LDSA at all locations. The relationship was mainly linear in traffic-dominated settings, and as BC concentration increased, the LDSA increased in a similar fashion.

One of the most important results of this research is that BC is a disproportional contributor to LDSA relative to its contribution to the mass of the particle. The proportion of LDSA to the BC emissions was reported as 33% in the street canyon, 30% on the highway, and 47% in the harbour, compared to the much lower proportion of BC to PM_{10} mass, at 14, 14 and 7, respectively (Lepistö

et al.). This difference suggests that BC is a dominant factor in the determination of biologically relevant exposure, despite its comparatively minor contribution to overall particulate mass. Other environmental evidence supports this relationship. Equivalent black carbon (eBC) has been shown to be significantly associated with LDSA in harbour settings impacted by marine traffic, and in residential settings where wood combustion emissions are prevalent (Hama et al., 2017; Cheristanidis et al., 2020). Mukherjee et al. found a very strong correlation between LDSA and eBC in flaming combustion conditions, with an R^2 value of 0.93, which underscores the role of combustion-generated particles in the concentration of LDSA.

The predictive value of BC in estimating LDSA is also confirmed by studies of statistical modelling. Fung et al. proved that BC is one of the most powerful predictors of LDSA in urban areas, along with $PM_{2.5}$ and particle number concentration. Mixed-effects models that included these variables had R^2 values of 0.77 to 0.80 in the estimation of LDSA at street canyon and urban background locations in Helsinki. All these results suggest that BC is a strong and stable predictor of LDSA in diverse combustion-contaminated conditions. It should be noted though that most of these studies have been carried out in ambient conditions where atmospheric mixing and aging processes take place. It is not clear how far these relationships can be extended to confined and ventilation-driven environments like underground mines and there is therefore a need to investigate further under such conditions.

A significant aspect of the BC-LDSA association is that black carbon (BC) particles are not only involved in the development of the alveolar surface area, but also as a carrier of toxic substances to the deepest parts of the lung. As the diesel exhaust is diluted and cooled, the gaseous species (polycyclic aromatic hydrocarbons, volatile organic compounds, and other products of combustion) condense onto the surfaces of the BC particles at first (Lepistö et al.). This process not only enhances the effective particle size and surface area, but also enriches BC particles with adsorbed toxic materials. This is also known as the Trojan horse effect, whereby BC particles are able to bypass the upper airway defences and deposit directly in the alveolar region, where gas exchange takes place and systemic absorption is most effective (Ortega et al., 2014). Consequently, the health effect of BC is not confined to its own surface interactions but is enhanced by the fact that it delivers co-transported toxic substances to the delicate lung tissue. The implications of this mechanism on the interpretation of the relationship between BC and LDSA in exposure assessment

are important. The surface area that is related to a certain BC mass concentration is not predetermined but varies with the level of condensation of other co-emitted species, the aerosol aging state, and the chemical composition of the emissions. As a result, the same concentration of BC masses can be associated with significantly different LDSA values in various circumstances.

This inconsistency is depicted by the results of Lepisto et al., who compared the relationships between BC and LDSA in various settings. The LDSA per unit BC mass was observed to be about 2.4 to 2.7 times greater in harbour environments where emissions are rich in sulphur dioxide, nitrogen oxides and volatile organic compounds compared to road traffic environments. This implies that marine sources of BC may cause much greater biologically relevant exposure than an equal mass of BC in traffic sources, because of increased condensation and particle growth.

These findings highlight that the BC–LDSA relationship is influenced not only by particle size but also by particle composition and transformation processes. This has important implications for applying BC as a proxy for LDSA, particularly in environments where emission characteristics and aerosol conditions differ from those in which empirical relationships have been established.

Underground mines differ fundamentally from ambient environments in several key aspects that may influence the BC–LDSA relationship. First, diesel emissions in mines are predominantly fresh, with minimal atmospheric aging. The confined geometry and short residence times limit condensation and coagulation processes that typically modify particle size distributions in outdoor environments. Based on findings from combustion studies, this suggests that BC–LDSA relationships in mines may be more direct and potentially more linear than in aged urban aerosol, where secondary processes introduce additional variability. At the same time, the confined nature of underground mine workings restricts pollutant dispersion and limits dilution by ambient air. As a result, diesel particulate matter can accumulate within the drift, producing concentration levels significantly higher than those observed in outdoor environments (Kimbal et al.). Whether the BC–LDSA relationship remains linear and predictable under such elevated concentration conditions is not well understood and requires investigation.

In addition, underground mine atmospheres include aerosol sources that are not present in typical urban traffic environments. Mineral dust generated from rock fragmentation and blasting, as well as blasting-related emissions, contribute to the overall particulate mixture. The extent to which these non-diesel particles influence LDSA and potentially modify the relationship between BC and LDSA has not been systematically evaluated. Ventilation systems introduce a further level of complexity. Mechanically driven airflow creates non-uniform velocity fields, recirculation zones, and spatial concentration gradients within the mine. These flow structures influence pollutant transport and distribution, resulting in localized regions of elevated exposure that cannot be captured by averaged measurements (Salo et al.). Consequently, the BC–LDSA relationship may vary significantly across different locations within the same drift.

Taken together, these factors indicate that BC–LDSA relationships established in ambient environments cannot be directly transferred to underground mine conditions without validation. In particular, understanding how BC and LDSA vary spatially within a ventilated mine drift is essential for determining whether BC can be used as a reliable proxy for health-relevant exposure. Addressing this need forms the central objective of the present study, which applies a spatial analysis framework to investigate the relationship between BC and LDSA under controlled underground ventilation conditions.

3. METHODOLOGY

The methodology used in this research is intended for the investigation of the spatial distribution of diesel particulate matter (DPM) and its correlation with black carbon (BC) and lung-deposited surface area (LDSA) in an underground mine. A computational fluid dynamics (CFD) method is used for simulating the airflow in a mechanically ventilated mine drift.

The modelling framework integrates geometric representation of the mine drift, numerical simulation of airflow and scalar transport, and post-processing techniques for the extraction of BC concentration and estimation of LDSA. The study combines physical modelling of diesel emissions with numerical solution methods to evaluate pollutant dispersion and assess potential exposure risks.

The methodology has various key components, such as geometric modeling, computation of the domain, governing equations, mesh generation, specification of the boundary conditions, modelling of diesel particulates, data extraction, and risk assessment for hazard zones mapping. The integrated approach allows for the thorough analysis of the air flow, the pollutant transportation mechanism, and the resultant health-related exposure.

3.1 Geometry of the Mine Drift

The computational domain was constructed to represent a simplified underground metalliferous mine drift operating under mechanically ventilated conditions. The geometry is composed of a rectangular tunnel with an overall length of 50 m and constant cross-section dimensions of 4.4 m width and 4.4 m height. The dimensions are characteristic of the underground mine workings where diesel-powered machinery is commonly used. A coordinate system was established along the longitudinal axis of the tunnel, with the ventilation inlet located at the origin ($x = 0$ m) and the outlet located at ($x = 50$ m). The coordinate system definition allows for the spatial analysis of the ventilation behavior. The ventilation was performed through the use of two auxiliary ducts placed along the ceiling and oriented along the longitudinal axis of the tunnel.

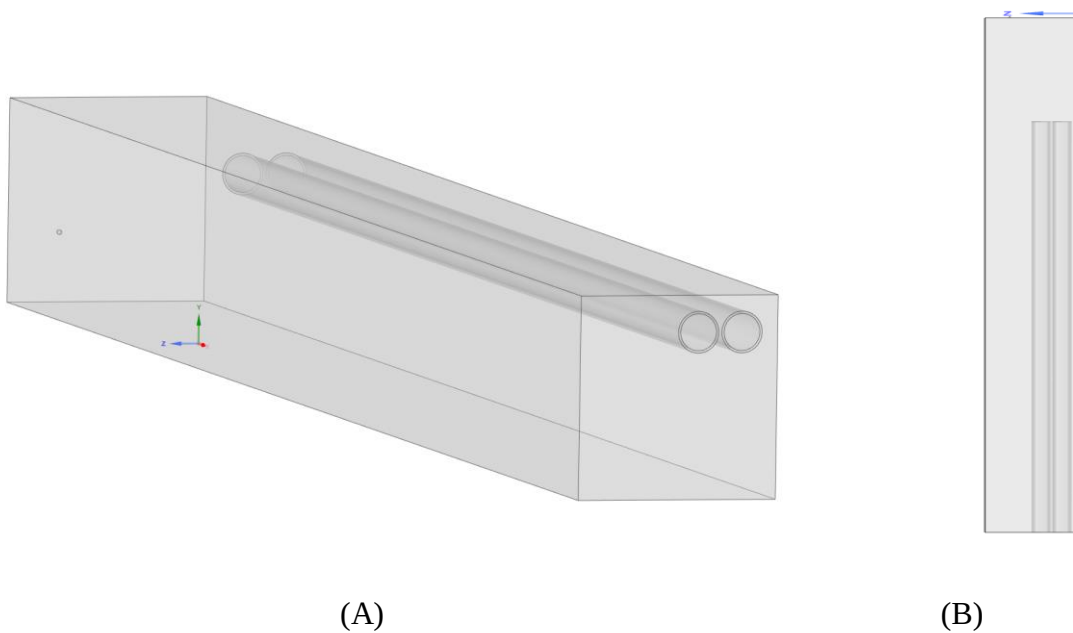


Figure 1. Geometry of the mine drift Isometric view (A) & Plan view (B)

The three-dimensional computational geometry of the mine drift and auxiliary ventilation ducts, is illustrated in Figure 1.

Each duct has a length of 40 m, an internal diameter of 0.8 m, and a wall thickness of 0.01 m. The ducts operate as supply air systems, delivering high-velocity airflow toward the working face region. The discharged airflow forms a primary jet along the tunnel axis, which interacts with the surrounding boundaries and generates recirculation zones and return flow within the domain. Such flow features are characteristic of auxiliary ventilation systems in underground mine environments. A cross-sectional representation of the computational domain, including tunnel dimensions and auxiliary duct configuration, is presented in Figure 2.

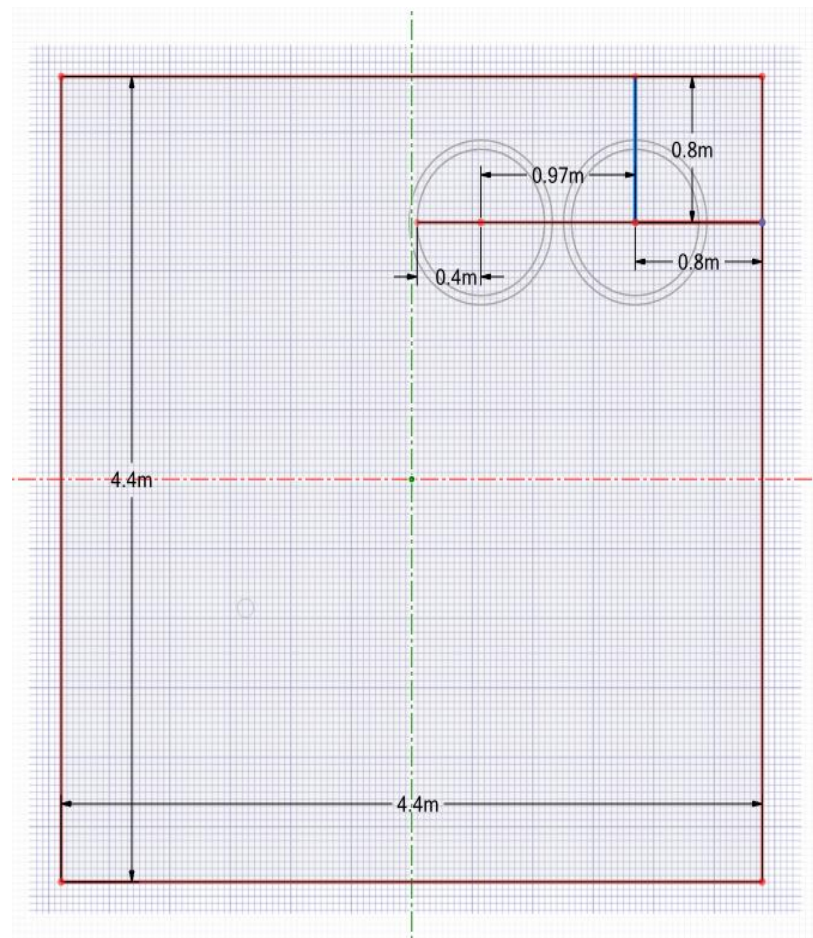


Figure 2. Cross-sectional geometry of auxiliary ventilation ducts relative to the tunnel boundaries

The diesel emission source was represented by a Load–Haul–Dump (LHD) vehicle located near the central region of the drift. The exhaust outlet was modelled as a circular opening with a

diameter of 0.1 m, positioned near the left wall at a height of 0.4 m above the floor (Caterpillar Inc., n.d.).

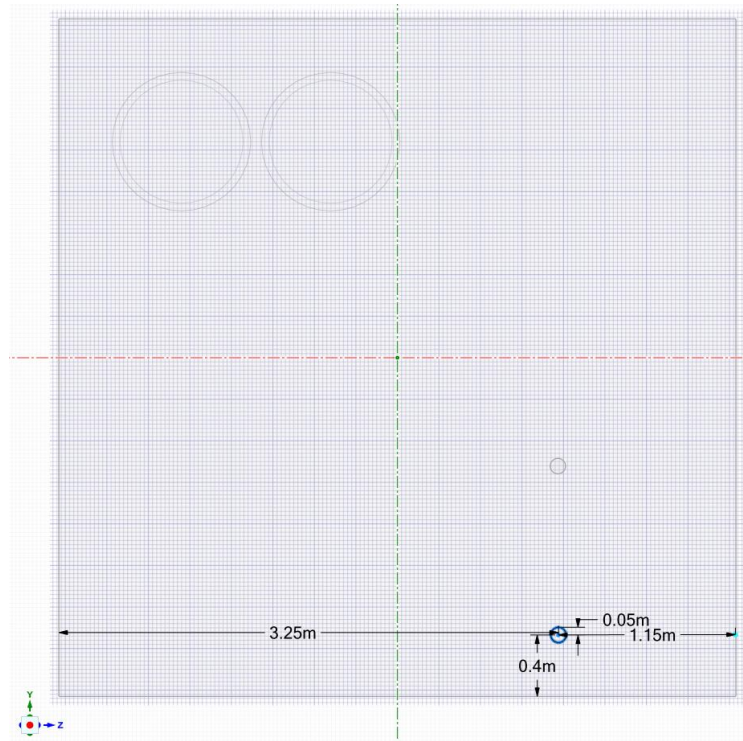


Figure 3. Cross-sectional geometry of the emission source relative to the tunnel boundaries

A single emission source was considered to isolate the effect of diesel particulate release on airflow patterns and concentration distribution. The tunnel was modelled as an empty domain without additional equipment or obstructions. This simplification is commonly adopted in CFD studies to reduce geometric complexity while preserving the dominant airflow structures governing pollutant transport, including jet development, recirculation, and backflow within the mine drift.

3.2 Computational and Numerical Implementation

3.2.1 Computational domain

The computational model was developed to simulate airflow and diesel particulate transport within the underground mine drift under simplified yet physically representative conditions. The airflow was considered to be in a steady-state condition. This helped in the

assessment of the spatial distribution of pollutants without having to consider transient changes. This is commonly used in CFD simulations to examine the dominant flow patterns in the system. The air inside the domain was modelled as an incompressible fluid with constant thermophysical properties: density - 1.225 kg/m^3 , a dynamic viscosity - $1.7894 \times 10^{-5} \text{ kg/(m*s)}$, a specific heat capacity - 1006.43 J/(kg*K) , and a thermal conductivity - 0.0242 W/(m*K) , based on the standard atmosphere conditions. The flow was modelled as isothermal with a constant temperature of 26.85 C , as the thermal effects were not included in the simulation.

The gravity acceleration was included in the model. It was set to a constant acceleration of -9.81 m/s^2 in the vertical direction (y). Even though the flow due to buoyancy was not analyzed in the current simulation, gravity was included to make the flow field physically consistent.

The flow regime within the drift was assumed to be fully turbulent, consistent with high-velocity ventilation airflow and jet development from the auxiliary ducts. Turbulence effects were therefore accounted for using an appropriate turbulence model, as described in a subsequent section. Diesel particulate matter was modelled as a passive scalar using the species transport approach, which is a commonly adopted method for representing particulate dispersion in ventilation-driven flows. Particle deposition, agglomeration, and chemical transformation processes were neglected. This assumption allows the study to focus on transport and dispersion mechanisms without introducing additional computational complexity associated with multiphase modelling.

The diesel emission source, representing the LHD exhaust, was assumed to be stationary and operating under constant emission conditions. This simplification enables controlled analysis of pollutant distribution and is consistent with steady-state modelling assumptions adopted in this study.

3.2.2 Numerical equations

The airflow and pollutant transport within the mine drift were modelled using the governing equations of fluid flow and scalar transport within a steady-state, incompressible flow framework.

According to Versteeg and Malalasekera (2007), the conservation of mass within the flow domain is described by the continuity equation:

$$\nabla \cdot u = 0 \quad (1)$$

The airflow field is governed by the momentum conservation equation (Versteeg & Malalasekera, 2007; ANSYS, 2021):

$$\rho(u \cdot \nabla) = -\nabla p + \mu \nabla^2 u + \rho g \quad (2)$$

The transport of diesel particulate matter, represented as a passive scalar surrogate for black carbon, is modelled using the species transport equation. Since no chemical reactions are considered, scalar transport is governed by convection and diffusion (Ferziger & Perić, 2002):

$$\nabla \cdot (\rho u Y) = \nabla \cdot (\rho D \nabla Y) \quad (3)$$

Where:

ρ - fluid density (kg/m³)

u - velocity vector (m/s)

p - pressure (Pa)

μ - dynamic viscosity (kg/m*s)

g - gravitational acceleration (m/s²)

Y - mass fraction of diesel particulate matter

D - mass diffusivity of species (m²/s)

The parameters used in the governing equations are defined as follows: fluid density ($\rho = 1.225 \text{ kg/m}^3$), dynamic viscosity ($\mu = 1.789 \times 10^{-5} \text{ kg/(m*s)}$), and gravitational acceleration ($g = 9.81 \text{ m/s}^2$), corresponding to standard atmospheric conditions. The velocity field (u) and pressure (p) are obtained as part of the CFD solution. The mass fraction (Y) represents the local concentration of diesel particulate matter and varies throughout the domain. The mass diffusivity (D) was assumed to be $1 \times 10^{-5} \text{ m}^2/\text{s}$ to represent scalar transport within the airflow. The species transport model is applied without chemical reactions, consistent with the assumption that diesel

particulate matter behaves as a passive scalar within the airflow. These equations form the basis for modelling airflow and pollutant dispersion within the mine drift.

3.3 Mesh Generation and Turbulence Modelling

The discretization of the computational domain was done by creating an unstructured tetrahedral mesh, which was generated using the ANSYS Meshing software, which is widely used for complex geometries, especially in three-dimensional domains. The final mesh had 747,294 elements and 145,352 nodes, which were adequate for the simulation of airflow structures and pollutant transfer within the mine drift. The generation of the mesh was done using adaptive sizing, which had a resolution level of 7, allowing for refinement of the mesh according to the geometric complexity of the domain. The global face sizing was set to 0.2 m to ensure uniformity of the elements within the domain. The choice of linear elements was made to ensure computational efficiency while maintaining the accuracy for large three-dimensional domains (Versteeg & Malalasekera, 2007).

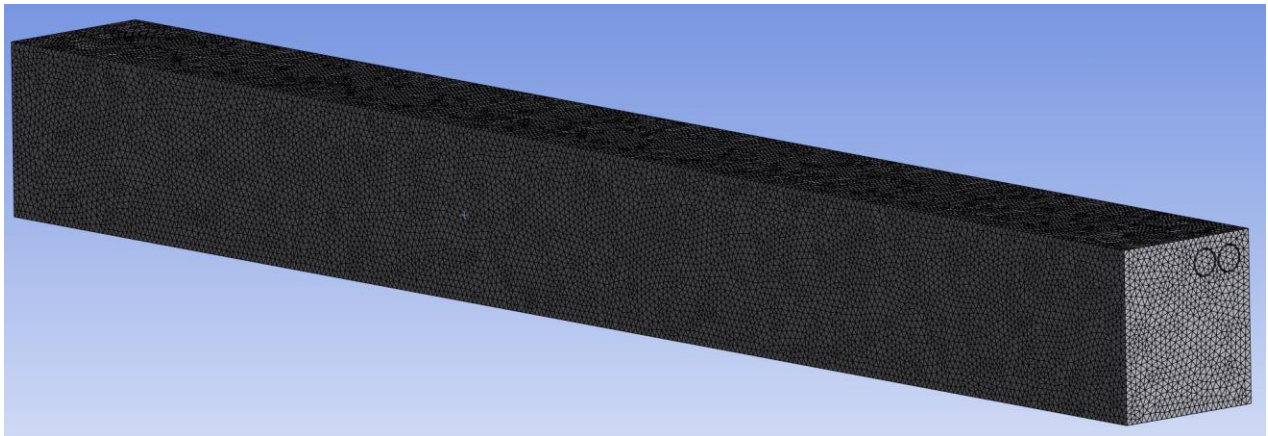


Figure 4. Computational mesh of the mine drift

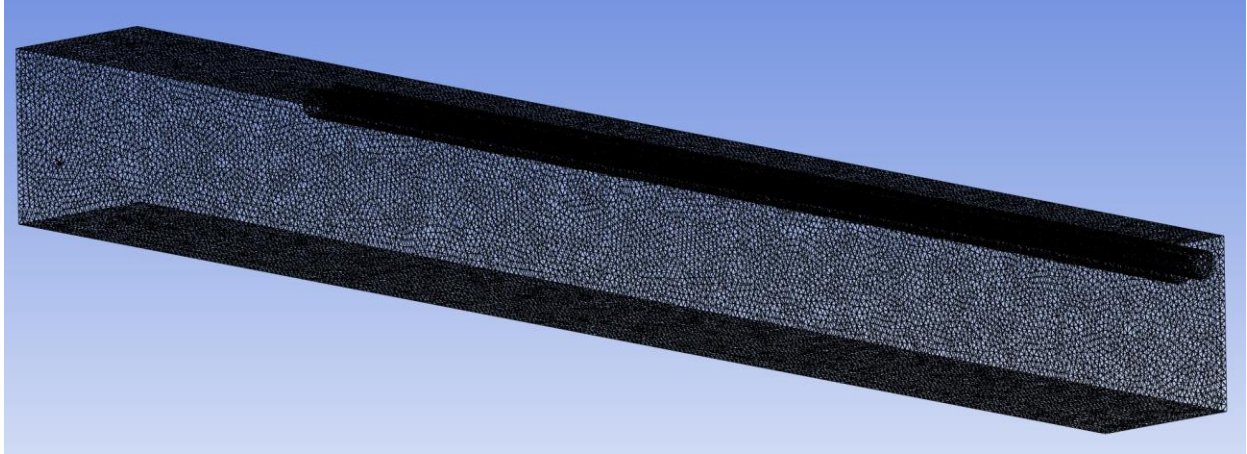


Figure 5. Computational mesh of the mine drift illustrating internal ventilation ducts

The generated computational mesh, including refinement near the ventilation ducts and internal regions, is illustrated in Figure 5. Mesh quality was evaluated using standard metrics, including skewness and element quality. The majority of elements exhibited skewness values below 0.25, indicating good mesh quality across most of the domain. The maximum skewness was 0.7, which is within acceptable limits for tetrahedral meshes, although it shows the presence of a small number of skewed elements. The minimum element quality was 0.45. While these values indicate localized regions of lower mesh quality, they are not expected to significantly affect the overall solution accuracy, as the majority of elements satisfy recommended quality thresholds for CFD applications showing element quality over 0.8. The maximum aspect ratio of approximately 15.4 was also considered acceptable.

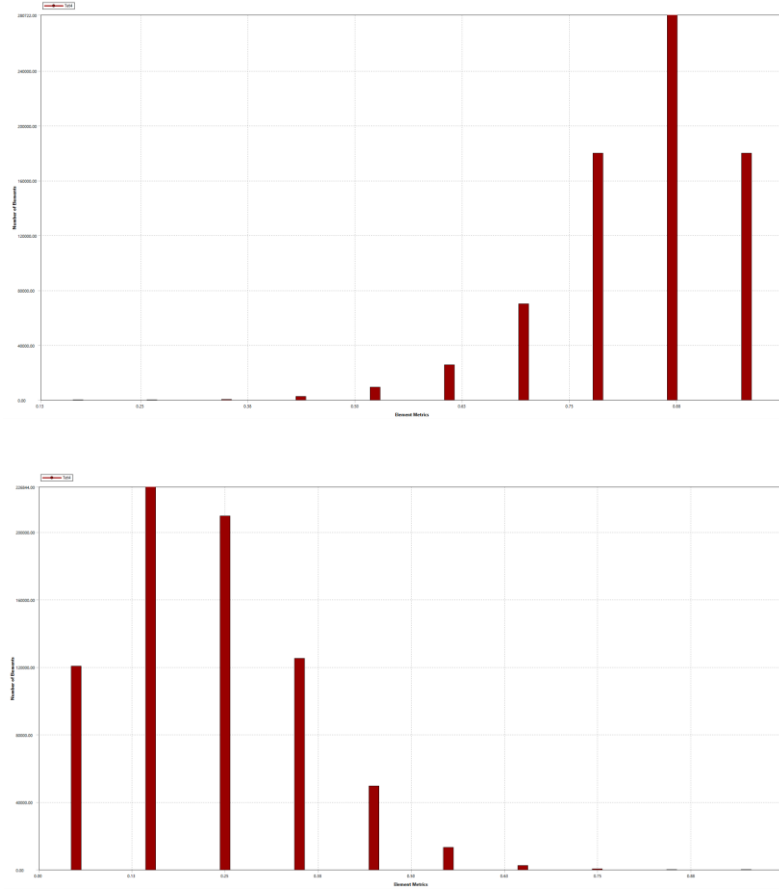


Figure 6. Histograms of mesh elements quality and mesh skewness

Distribution of element quality, demonstrating that the majority of elements are within acceptable and high-quality ranges, and the skewness distribution of the mesh is shown in Figure 6.

Minimum inflation layers were applied, as the study focused on bulk airflow behavior and scalar transport rather than near-wall boundary layer effects. The mesh was therefore optimized to resolve dominant flow features, including jet development from the ventilation ducts and recirculation zones within the drift. The selected mesh resolution was chosen based on sensitivity to key flow features and is consistent with mesh densities commonly used in similar CFD studies of mine ventilation (Ferziger & Perić, 2002). The mesh was therefore considered sufficient to capture the dominant flow behavior and concentration gradients within the domain.

The turbulent airflow within the mine drift was modelled using the realizable $k-\epsilon$ turbulence model, which is widely applied in CFD simulations of ventilation and confined flows.

This model provides improved performance in predicting flow separation, recirculation, and jet behavior compared to the standard $k-\epsilon$ model. The realizable $k-\epsilon$ model solves two additional transport equations for the turbulent kinetic energy (k) and its dissipation rate (ϵ), enabling representation of turbulence effects within the flow field. This approach is suitable for the present study, where high-velocity airflow from ventilation ducts generates complex flow structures, including jet development and recirculation zones (Versteeg & Malalasekera, 2007; ANSYS, 2021). Enhanced wall treatment was applied to improve the accuracy of near-wall flow modelling. This approach combines a two-layer model with wall functions, allowing the solution to adapt to the local mesh resolution near solid boundaries. It provides improved prediction of velocity gradients and turbulence behavior in regions close to the tunnel walls compared to standard wall functions. The selection of the realizable $k-\epsilon$ model with enhanced wall treatment was based on its balance between computational efficiency and accuracy for industrial-scale turbulent flows. It is particularly suitable for ventilation-driven flows where jet development and recirculation are dominant.

Despite its advantages, the model assumes isotropic turbulence and may have limitations in accurately resolving highly anisotropic or transient flow structures. However, for steady-state simulations of ventilation flow and pollutant dispersion, it provides an appropriate representation of turbulence behavior.

3.4 Boundary Conditions and CFD Solution configuration

3.4.1 Boundary conditions

Boundary conditions were specified to represent the ventilation system and diesel emission source within the mine drift. Airflow was introduced into the domain through two auxiliary ventilation ducts modelled as velocity inlets. Both ducts were assigned a uniform velocity magnitude of 17 m/s directed normal to the inlet boundary, consistent with typical auxiliary ventilation systems in underground mines (Hartman et al., 2012; NIOSH, 2019; Qureshi et al., 2025). Turbulence at the inlet was specified using the turbulence intensity and viscosity ratio approach, with a turbulence intensity of 5% and a turbulent viscosity ratio of 5. At the outlet of the drift, a pressure outlet boundary condition was applied with a gauge pressure of 0 Pa, which is commonly used for ventilation flow simulations. Backflow conditions were prescribed using the

same turbulence parameters as the inlet, allowing the model to handle reverse flow associated with recirculation within the tunnel.

The diesel emission source was modelled as a mass-flow inlet representing the exhaust emission from the LHD. Turbulence at the emission source was defined using a turbulence intensity of 10% and a turbulent viscosity ratio of 10, reflecting the higher turbulent exhaust flow. All boundary conditions were applied with the steady-state and isothermal properties described in the computational model.

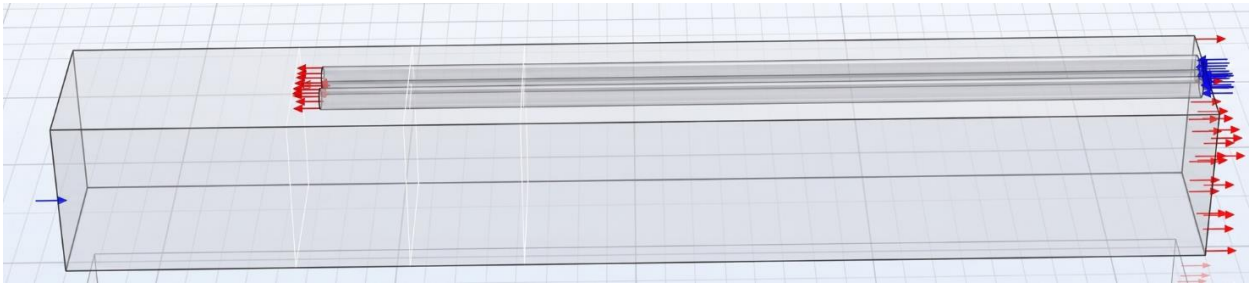


Figure 7. Visualization of boundary conditions in the computational domain, including velocity inlets and pressure outlets

The applied boundary conditions, including airflow inlets through the ventilation ducts (blue arrows), the outlets (red arrows) at the drift exit and mass flow inlet at the working face (blue arrow), are presented in Figure 7.

3.4.2 Numerical solver configuration

The numerical simulation was performed using a pressure-based steady-state solver, which is commonly applied for incompressible ventilation and internal flow applications. Pressure-velocity coupling was achieved using the SIMPLE algorithm, providing a stable and efficient solution for steady-state conditions (Versteeg & Malalasekera, 2007). Spatial discretization was carried out using second-order schemes to improve solution accuracy. Momentum, turbulent kinetic energy (k), turbulent dissipation rate (ϵ), and species transport equations were discretized using second-order upwind schemes. The pressure field was discretized using the body force weighted scheme, suitable for flows influenced by gravity. Gradient calculations were performed using the least squares cell-based method. Most parameters were taken as default, such as 0.3

pressure, 0.5 momentum, 0.5 turbulent kinetic energy and dissipation rate, and 0.7 turbulent viscosity and species transport (Versteeg & Malalasekera, 2007; ANSYS, 2021).

Standard initialization was used to initialize the solution, where velocity is initialized in the axial direction and all the scalar species such as $h\nu_{vol}$ are initialized to zero. The first temperature was held at 26.5 C, which is in line with the assumption of isothermality. The convergence of the solution was checked by the residuals of the governing equations. The convergence criteria were established to 10^{-6} in continuity, momentum, quantities of turbulence and energy equations and 10^{-3} in species transport equations (ANSYS, 2021). The simulation was repeated around 500 times and the residuals were found to stabilize and no significant changes in the solution variables were found which indicated that the numerical solution had converged.

3.5 Emission source modelling

The diesel emission source within the computational domain was defined based on the specifications of a representative underground Load–Haul–Dump (LHD) machine. A Caterpillar R1700 LHD was selected due to its widespread use in underground mining operations and its relevance to diesel particulate emissions in confined environments. The selected LHD is equipped with a Cat® C13 diesel engine with a rated power output of 345 hp, which was converted to SI units to ensure consistency with the computational model (Caterpillar Inc., n.d.):

$$P = 345 \text{ hp} * 0.7457 \frac{\text{kW}}{\text{hp}} = 257 \text{ kW} \quad (4)$$

The fuel consumption of the engine was estimated using a typical brake-specific fuel consumption (BSFC) value for diesel engines operating under steady conditions. A BSFC of 210 g/kWh was assumed, consistent with reported values for heavy-duty diesel engines (Heywood, 2018). The fuel consumption rate was calculated as:

$$m_{fuel} = P * BSFC \quad (5)$$

The emission of diesel particulate matter was estimated using an emission factor expressed in terms of mass per unit energy output. A representative emission factor of 0.2 g/kWh was adopted

based on reported values for diesel particulate emissions from heavy-duty diesel engines in underground mining environments (USEPA, 2004).

The particulate emission rate was calculated as:

$$m_{DPM} = P * EF \quad (6)$$

The resulting emission rate was converted from g/h to kg/s to match the requirements of the CFD model:

$$m_{DPM} = \frac{P * EF}{3600 * 1000} \quad (7)$$

Where:

P — engine power (kW)

$BSFC$ — brake-specific fuel consumption (g/kWh)

EF — emission factor for diesel particulate matter (g/kWh)

m_{fuel} — fuel consumption rate (g/h)

m_{DPM} — diesel particulate emission rate (kg/s)

The final calculated mass flow rate of diesel particulate matter was approximately $1.4 * 10^{-5}$ kg/s. The calculation assumes that the engine operates at rated power under steady conditions. In practical underground mining operations, engine load varies depending on duty cycles, which may result in lower emission rates than those estimated under full-load conditions. To account for this, the mass flow rate was conservatively reduced by 25% to better represent typical operating conditions. This adjusted value was then applied as the mass-flow inlet boundary condition representing the exhaust emission from the LHD within the computational domain. The emission was assumed to be constant over time and uniformly distributed across the exhaust outlet, consistent with the steady-state modelling approach adopted in this study.

The transport of diesel particulate matter within the mine drift was modelled using the species transport approach. Diesel particulate matter was represented as a passive scalar species, serving as a surrogate for black carbon, which is commonly used to represent diesel particulate emissions in underground mining studies. A single scalar species, defined as a surrogate variable

(hv_vol), was introduced to represent the diesel particulate phase within the airflow. Transport of the scalar species was governed by convection and diffusion processes. Convection represents transport of particulate matter by the airflow, while diffusion accounts for spreading due to concentration gradients. A constant mass diffusivity of $2.88 \times 10^{-5} \text{ m}^2/\text{s}$ was specified by the software.

It was assumed that no chemical reactions, phase changes, or particle interactions, including deposition or agglomeration, were involved. This allowed the diesel particulate matter to be used as a passive tracer to analyze the spatial distribution of the diesel particulate matter within the mine drift.

3.6 LDSA Data Extraction Procedure

The distribution of diesel particulate matter was analyzed based on concentration data extracted from the CFD simulation. Spatial variation in pollutant concentration was evaluated using contour planes located at three positions along the drift: 10 m, 15 m, and 20 m from the working face. These planes were used to evaluate and compare the spatial distribution of pollutants at increasing distances from the emission source. Also, the concentration profiles were sampled along six longitudinal lines (x-axis direction) that were placed to sample the variation across the tunnel cross-section at two heights. The initial three lines were placed at 1.5 m above the floor which is the average breathing zone of underground workers, and on the left wall, at the centre and on the right wall. The second set of three lines was determined at 2.2 m height with the same lateral positions. This dual-height configuration enabled analysis of both horizontal and vertical variation

in pollutant distribution, with particular emphasis on worker breathing zone exposure.

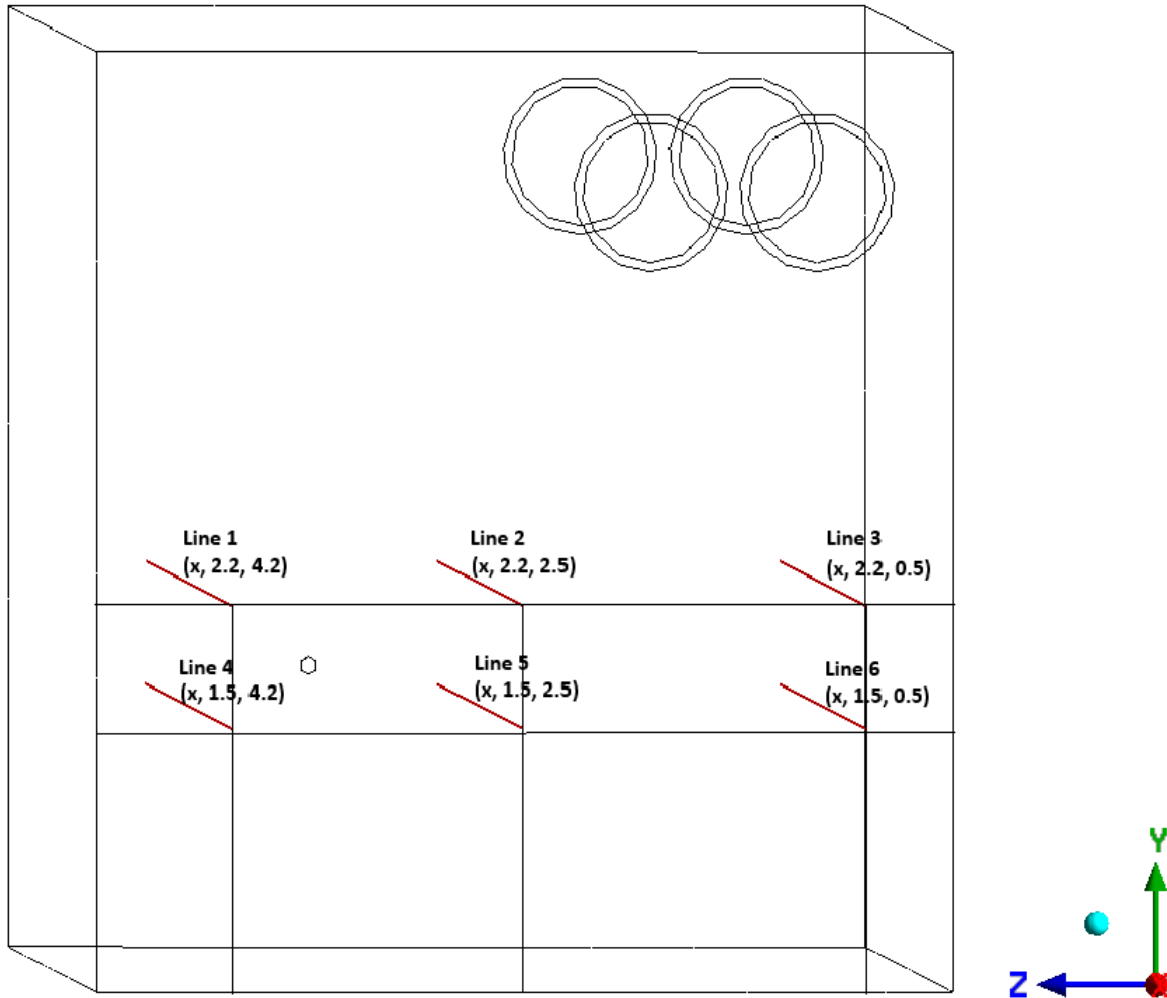


Figure 8. Visualization of monitoring lines across the drift

The primary output from the CFD simulation is a mass fraction field ($h\nu_{vol}$) that represents the spatial distribution of diesel particulate matter throughout the computational domain. The mass fraction is defined as the ratio of pollutant mass to the total mass of the air-particle mixture:

$$Y_{h\nu_{vol}} = \frac{m_{pollutant}}{m_{air} + m_{pollutant}} \quad (8)$$

This mass fraction field is the fundamental variable that is solved by the CFD model, which is the result of a numerical solution of the passive scalar species transport equation (Equation 3, Section 3.2.2). Development of the mass fraction field is determined by two physical processes including (1) convection which is the process of transport of the mass of pollutants by the velocity field, and (2) turbulent diffusion which is the process of spreading the pollutant as a result of turbulent mixing and concentration gradients. Because the pollutant was modelled as a passive scalar, it does not influence the airflow field and is transported solely by the existing flow structures determined by the momentum and turbulence equations.

The mass fraction field thus provides a normalized spatial representation of pollutant concentration throughout the drift. While inherently dimensionless, the mass fraction at any point in the domain is directly proportional to the actual mass concentration of pollutant at that location, since it is obtained through division of pollutant mass by total fluid mass. This proportionality is the physical foundation that justifies subsequent conversion of mass fraction to quantifiable concentration units, as described below.

The assumption underlying this approach is that the passive scalar mass fraction, as solved by the CFD model, accurately represents the spatial distribution of the emitted diesel particulate matter. This assumption is valid because: (1) the emission source is modeled as a defined mass flow rate, (2) turbulent transport and diffusion processes govern pollutant dispersion, (3) particle deposition and agglomeration are neglected (providing a conservative estimate of pollutant persistence), and (4) the spatial resolution of the computational mesh is sufficient to capture dominant flow structures controlling pollutant dispersion. Under these conditions, the mass fraction field is a physically meaningful representation of pollutant spatial distribution.

To translate the CFD-derived mass fraction field into practical and health-relevant exposure metrics, this study proposes a three-step conversion methodology. This approach is necessary because the CFD output (mass fraction) is dimensionless and does not directly correspond to exposure units, while occupational health assessment requires quantitative concentration values and biologically meaningful dose metrics. Each conversion step is justified based on physical principles, established relationships, and assumptions documented in this section.

Step 1: Mass Fraction to Black Carbon Concentration

The dimensionless mass fraction values are converted into black carbon (BC) concentration expressed in $\mu\text{g}/\text{m}^3$ using the relationship:

$$C_{BC} = Y_{hv-vol} * \rho_{air} * 10^9 \quad (9)$$

Where:

- C_{BC} is the black carbon concentration ($\mu\text{g}/\text{m}^3$)
- Y_{hv-vol} is the dimensionless mass fraction of the scalar species (-)
- ρ_{air} is the air density in the computational domain (kg/m^3) = 1.225 kg/m^3
- 10^9 is the conversion factor from kg/m^3 to $\mu\text{g}/\text{m}^3$

This conversion is based on the fundamental principle that mass fraction, though dimensionless, represents actual mass concentration when multiplied by the total fluid density.

Since the mass fraction: $Y_{hv-vol} = \frac{m_{pollutant}}{m_{air} + m_{pollutant}}$, then $m_{pollutant} = Y * m_{total} = Y * \rho_{air} * V$.

Therefore, the mass concentration of the pollutant is $C = Y * \rho_{air}$, which is then converted to $\mu\text{g}/\text{m}^3$ using the unit conversion factor. This conversion is standard in CFD post-processing and is applied uniformly across all spatial locations in the domain (Versteeg & Malalasekera, 2007).

This conversion assumes that the mass fraction of the passive scalar is identical to the mass concentration fraction of actual diesel particles. In reality, particle properties such as shape, size distribution, and density could introduce minor discrepancies, but these are neglected in the passive scalar approach (Section 3.2.1). It is also assumed that air density is constant throughout the domain (1.225 kg/m^3 at standard conditions), consistent with the incompressible flow assumption in the CFD model and the scalar mass fraction directly represents diesel particulate matter concentration without losses due to deposition or agglomeration.

Step 2: Black Carbon Concentration to Lung-Deposited Surface Area

The BC concentrations obtained from Step 1 are converted to lung-deposited surface area (LDSA) using an empirical linear relationship derived from field measurements in underground mining environments:

$$LDSA = \frac{BC - 421}{0.50} \quad (10)$$

Where:

- LDSA is the lung-deposited surface area ($\mu m^2/cm^3$)
- BC is the black carbon concentration ($\mu g/m^3$)
- The constants 421 and 0.50 are empirical coefficients from Sabanov et al. (2025)

The use of this empirical relationship is based on multiple supporting observations. On a physical basis, the BC-LDSA correlation exists because BC particles typically reside in the 30-300 nm size range, which corresponds to the particle sizes most efficiently deposited in the alveolar region of the respiratory tract. This size overlap is not coincidental but reflects fundamental respiratory physics, BC particles are precisely the fraction of diesel aerosol most efficiently delivered to the gas-exchange surface (Bond et al., 2013). Similar conditions were empirically validated, where relationship was obtained based on field measurements in an operational underground metalliferous mine (Sabanov et al., 2025). This is identical mining environment and source of emissions (diesel engines in confined geometry) as what is simulated in the current study. This analogy in the conditions gives the reason to apply their empirical model to the CFD simulation results. Furthermore, in several settings (traffic, harbor, residential combustion), it has been shown that BC and LDSA are strongly correlated (Lepistö et al., 2022; Hama et al., 2017), which proves that BC is a valid surrogate of health-relevant alveolar surface area dose. It is assumed that the empirical relationship obtained by field measurements in an underground mine, can be applied to the conditions of this study, which are simulated by CFD, particle properties (size distribution, morphology, composition) are close enough between the field mine environment (where the empirical relationship was obtained) and the CFD model domain (where it is applied).

3.7 Hazard Mapping Framework and Limitations

3.7.1 Hazard assessment

The hazard assessment of diesel particulate matter exposure was conducted based on the spatial distribution of Mass Fraction obtained from the CFD simulations. The assessment was performed using both planar and line-based data extraction methods. BC concentration fields obtained from contour planes located at 10 m, 15 m, and 20 m from the working face were used to evaluate spatial distribution patterns. In addition, concentration profiles along six longitudinal lines were analyzed to capture variations across the tunnel cross-section. Particular emphasis was placed on the height of 1.5 m above the floor, corresponding to the typical breathing zone of underground workers. This allows the assessment to directly reflect potential human exposure conditions. Comparison between different heights also provides insight into vertical variation in pollutant distribution.

In addition to BC concentration, lung-deposited surface area (LDSA) was incorporated into the risk assessment to account for the health relevance of ultrafine particles. LDSA values estimated by BC concentration were also examined alongside BC distributions. This provides a more comprehensive evaluation of risk. This approach is useful in identifying areas of high levels of exposure, comparing levels of pollutants at varying distances from the working face of the mine, as well as assessing health risks associated with diesel particulate matter in an underground mine.

3.7.2 Assumptions and Limitations

The present study is based on several simplifications that should be considered when interpreting the results. The airflow in the mine drift was modelled as steady-state, it means that time-dependent changes in ventilation conditions and emission rates were not included. In real underground mine, operating conditions are often transient, which may influence pollutant dispersion. Diesel particulate matter was modelled as a passive scalar. Processes such as particle agglomeration, deposition, and chemical transformation were not considered. While this approach simplifies the modelling, it may result in differences between the simulated and actual behavior of diesel particles. The simulation domain was based on the tunnel's geometry, which did not take into account the addition of further equipment, obstacles, etc. Although this approach is convenient for studying the flow in the tunnel, it could lead to discrepancies in the actual flow in the mining

environment. The emission source was assumed to be constant and based on the rated engine power of the selected LHD. In real operating conditions, engine load varies depending on duty cycles, which can result in fluctuations in emission rates.

Turbulence was modelled using the realizable $k-\epsilon$ model with enhanced wall treatment. Although this model provides reliable predictions for ventilation flows, it assumes isotropic turbulence and may not fully resolve highly complex or anisotropic flow structures. Ventilation conditions were idealized, with uniform airflow supplied through the ducts and no consideration of leakage, flow fluctuations, or interaction with other ventilation systems. Lung-deposited surface area (LDSA) was not directly simulated but estimated from black carbon concentration using a literature-based empirical relationship. This introduces uncertainty associated with the applicability of the correlation under the specific conditions of the present study. In addition, the surrogate scalar species (hv_vol) used to represent diesel particulate matter does not directly correspond to actual physical concentrations. Instead, it serves as a numerical representation of pollutant transport, and the resulting values require interpretation and conversion to real-world concentration metrics. This introduces an additional level of approximation in the modelling approach.

4. RESULTS

4.1 Velocity Field Characteristics

The velocity field inside the mine drift has non-uniform spatial distribution which is controlled by the interaction between the airflow introduced into the mine via the auxiliary ventilation ducts and the geometry of the surrounding tunnel. The air is introduced by two ducts that are symmetrically placed close to the roof of the drift, which causes an overall symmetric flow structure around the longitudinal axis. Figure 9 shows the general airflow pattern by displaying the streamlines of velocity in the computational domain.

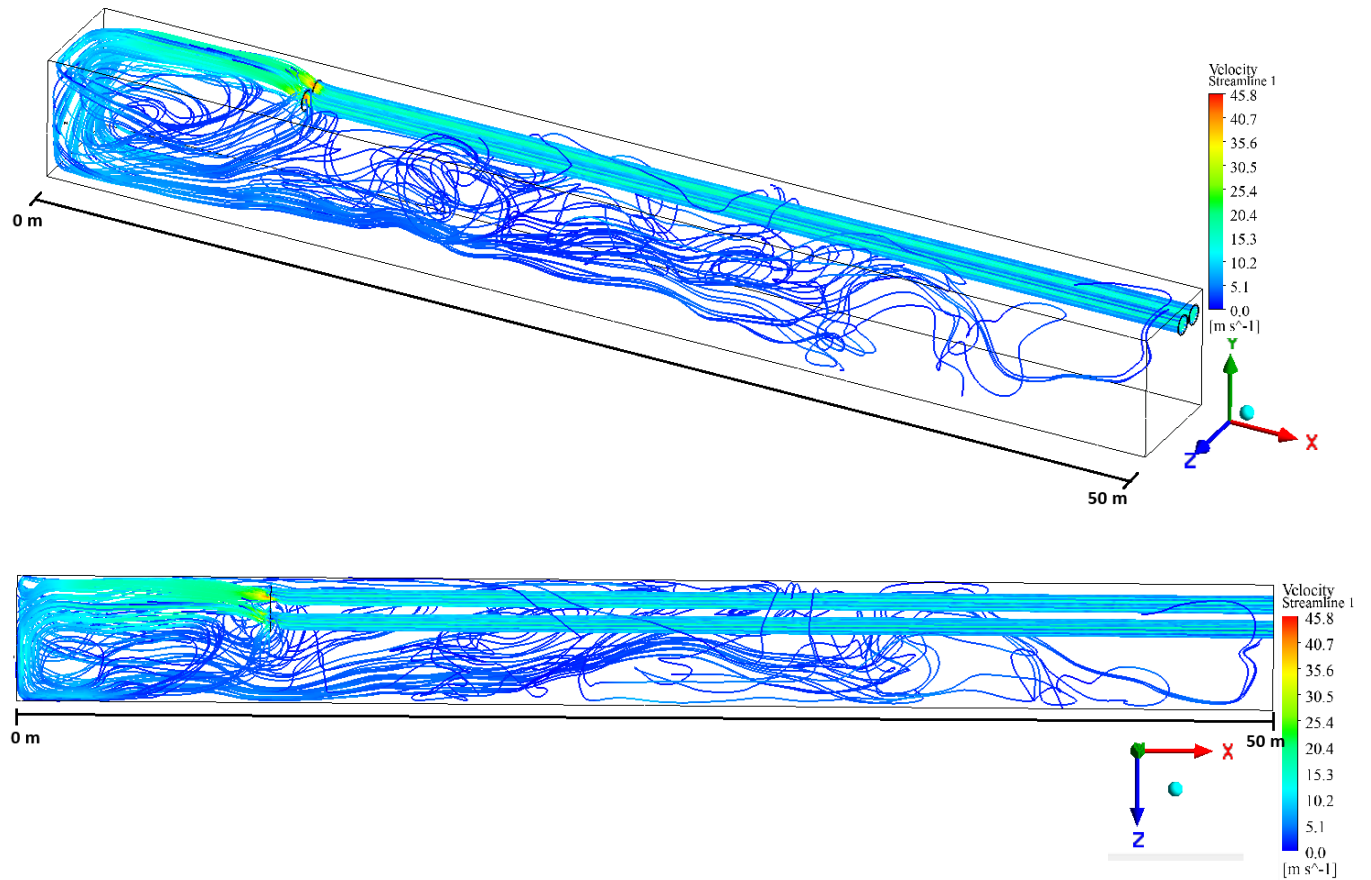


Figure 9. Velocity streamlines (Isometric (Upper figure) and Plan view (Below figure))

The largest magnitude of velocities is seen in the upper part of the tunnel, near the duct outlets, where air moves out of the confined duct geometry and into the drift. Peak velocities in these areas are 30-35 m/s, creating a high-momentum flow that is concentrated. This is a high velocity zone that runs along the upper section of the tunnel and forms the main way of airflow propagation. Outside the jet region, there is a progressive decrease in the magnitude of the velocities. Reduced velocity areas are seen along the tunnel boundaries, especially towards the side walls and in the lower parts of the drift. The floor area has moderate airflow, which implies that there is active but weaker flow than in the upper area. This creates a vertical gradient in the velocity distribution with more velocity at the roof and less at the floor.

The air flowing in the auxiliary ventilation ducts evolves into high velocity jet when it comes out of the duct outlets that are found about 10 m away of the working face. The airflow at the ducts is mostly linear but as it is discharged into the tunnel, the flow is expanded and it takes

the form of a concentrated jet in the higher part of the drift. As the air moves towards the working face, it strikes the upper corner of the tunnel boundary, leading to a major redistribution of momentum. When the working face is met, the airflow turns back, creating a strong backflow area. This inversion causes the air to flow downwards and on the other side of the drift, creating a backflow area. The high-momentum jet interacts with the solid boundary, resulting in a significant decrease in the local airflow momentum. Figure 10 shows the detailed structure of the backflow and vortex regions.

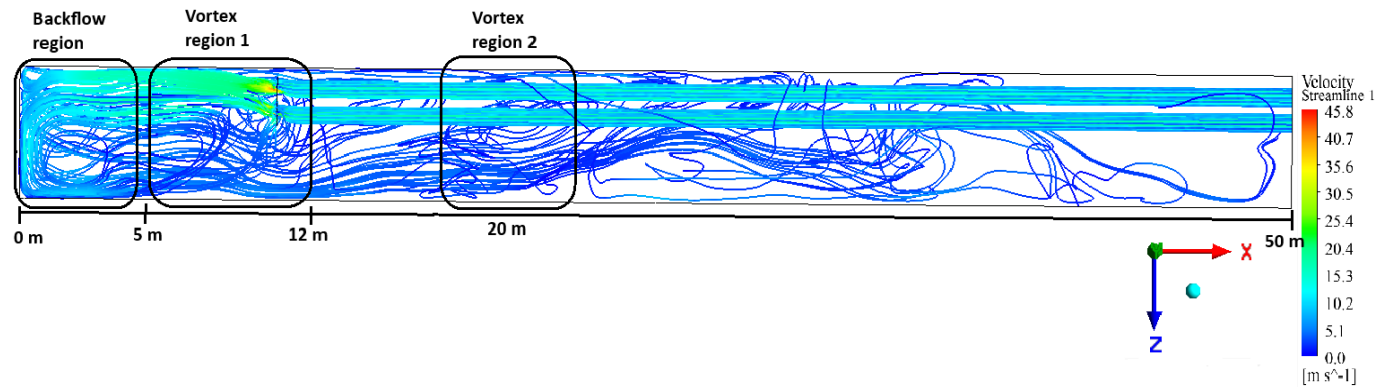


Figure 10. Annotated streamline showing backflow and vortex near working face

After the initial recirculation, the airflow restructures and moves downstream mainly in the mid-to-lower part of the drift. The interaction between the returning airflow and the residual jet momentum controls this flow, leading to a complex and spatially varying velocity field. Further downstream additional circulation structures are seen. The initial vortex area is determined around 5 m to 12 m away the working face, which implies that there is still mixing and redistribution of momentum in the drift. Farther down the stream, there is a weaker vortex area at around 20 m, which is indicative of the progressive decay of the main flow structures.

4.2 Velocity Distribution at Cross-Sectional Planes

The velocity distribution across the cross-section of the tunnel was measured at three points along the drift, i.e., at 10 m, 15 m and 20 m of the working face. These airflows give us an idea of how the airflow structure is changing spatially as it moves downstream. Figure 11 shows the velocity field at 10 m.

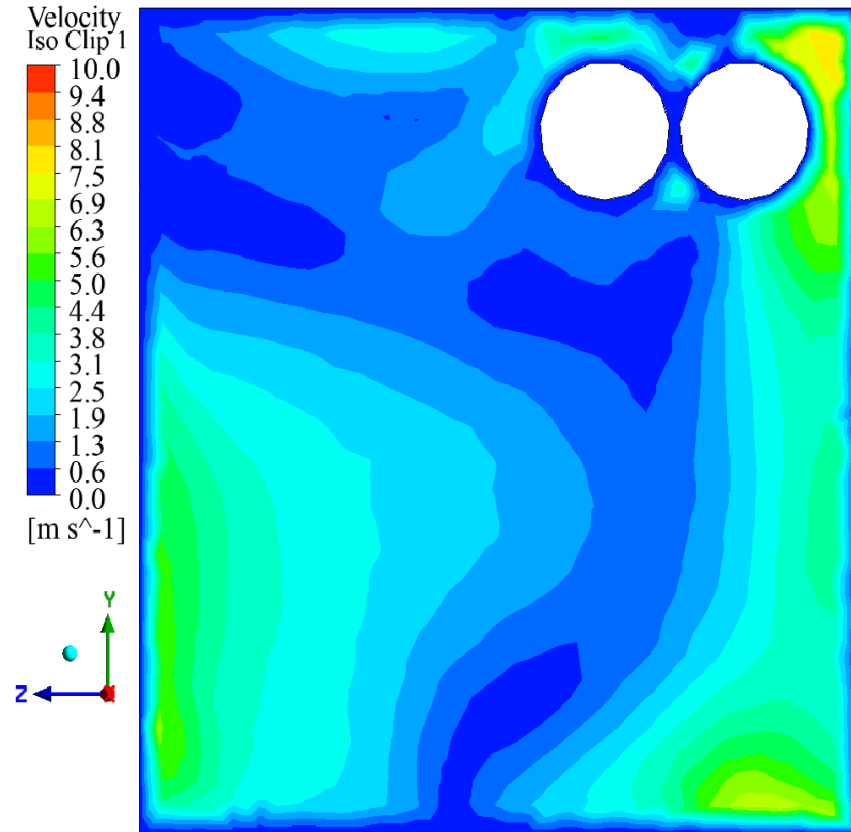


Figure 11. Velocity contour at 10 m plane

The high magnitudes of velocity are seen near the upper right side of the cross-section which is the location of the ventilation duct outlet and the incoming jet before it hits the working face reaching 9 m/s. Conversely, the lower values of velocity are located in the central area of the drift, which means that the intensity of flow is lower. The higher velocity is also seen on the left side of the cross-section (6-8 m/s), which is related to the returning airflow created by the backflow zone. The velocity distribution at this plane is hence highly non-uniform and represents the combined effect of both the incoming jet and the recirculation that is developing. Figure 12 illustrates a change in the structure of airflow at 15 m.

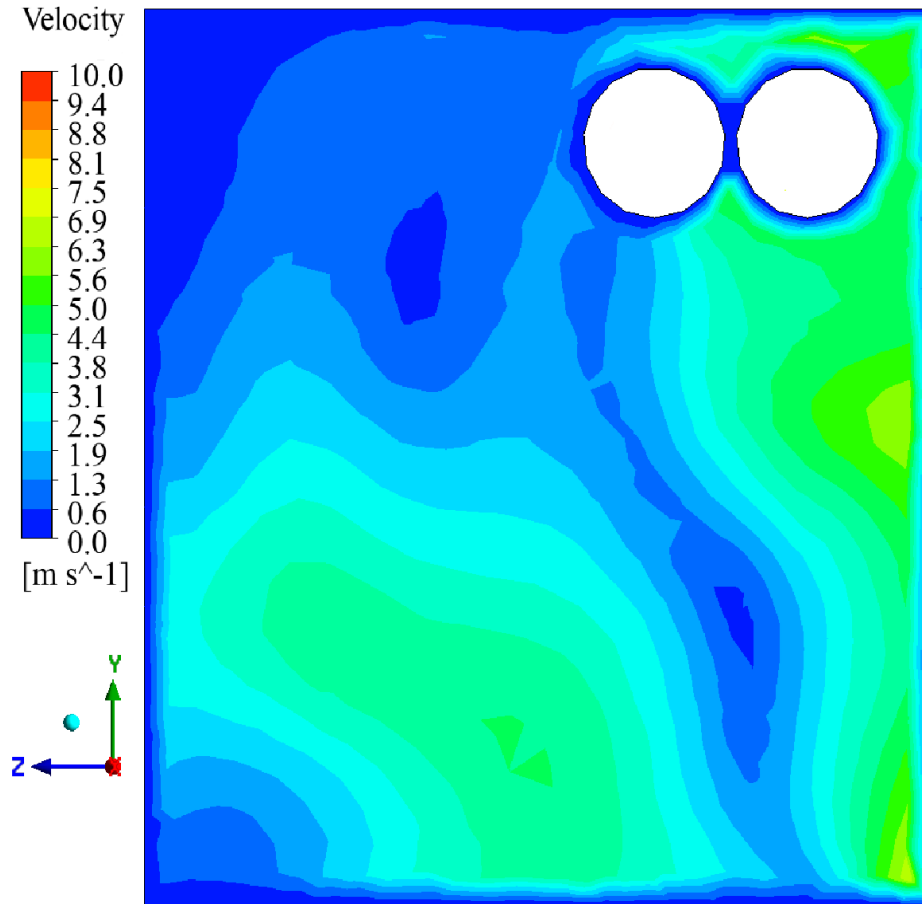


Figure 12. Velocity contour at 15 m plane

At this point, the effect of the original jet is less, and the air flow is more spread out over the cross-section. The high velocity zones are projected to the right-side wall to the lower part of the drift, reaching 6-7 m/s, and the middle zone has a higher velocity than that of the 10 m plane. The returning airflow is more prominent on the left side of the drift, which means that the recirculation structure is still developing. Velocity gradients across the cross-section are smaller, indicating a more equal distribution of airflow. The velocity field at 20 m is further downstream and is shown in Figure 13.

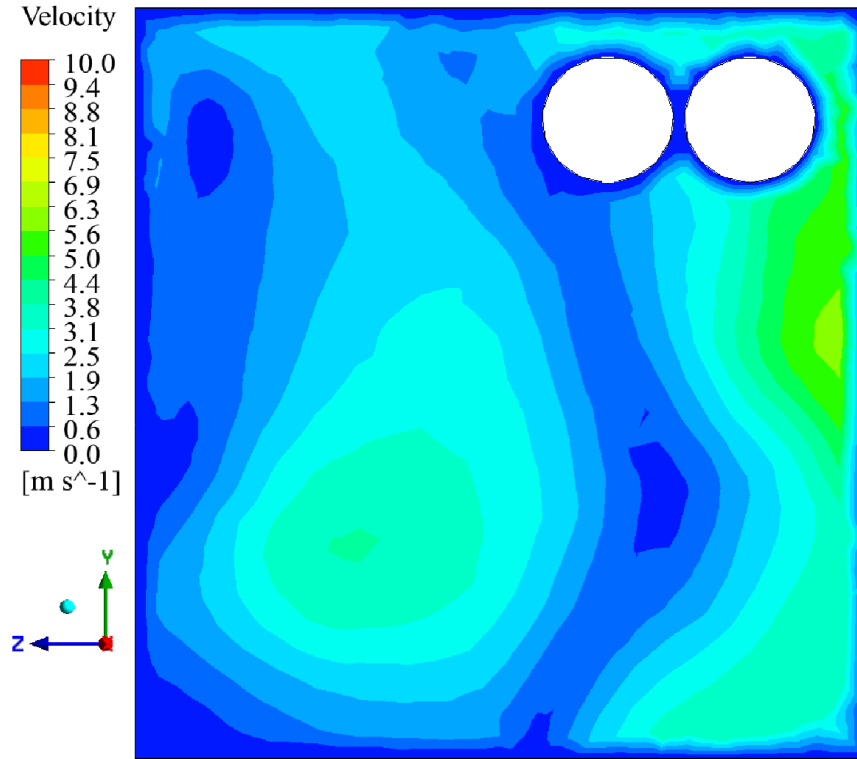


Figure 13. Velocity contour at 20 m plane

The velocity distribution at this plane is more homogeneous over the drift, and the magnitude of the velocity is moderate in the central area (5-6 m/s). The effect of the first jet is also reduced, but a little higher speed is still in contact with the wall on the right (6-7 m/s). There is a localized low-velocity area on the left side of the cross-section, which is a sign of the remaining effects of recirculation. The general airflow pattern indicates a reallocation of the momentum across the tunnel cross-section as the flow moves downstream.

4.3 Vertical Velocity Distribution (1.5 m and 2.2 m)

The change in airflow velocity with the height was measured in the longitudinal direction of the drift at two levels, i.e. 1.5 m above the tunnel floor and 2.2 m above the tunnel floor. These heights denote the breathing zone and an upper part of the drift, respectively, and give an idea of the vertical distribution of airflow in the domain. The velocity distribution at 1.5 m is presented in Figure 14.

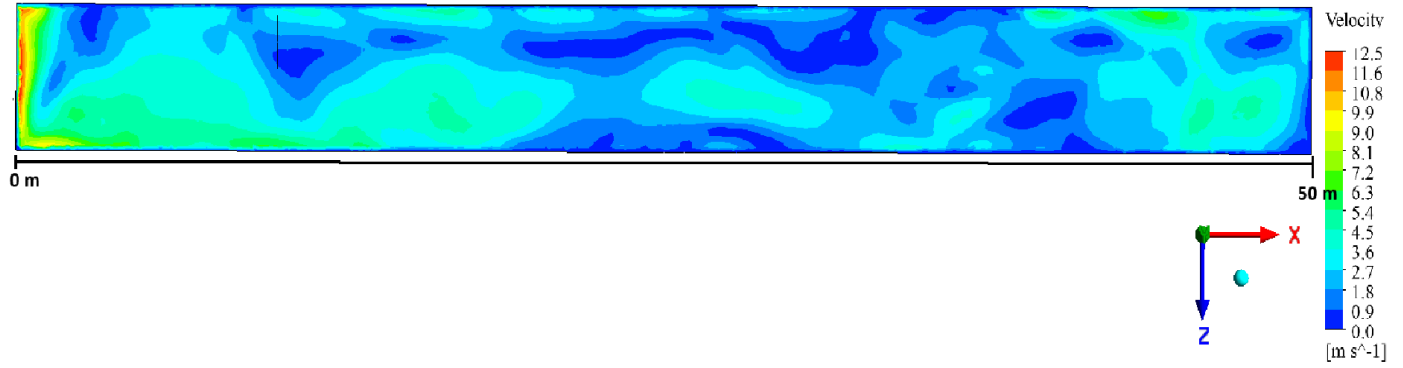


Figure 14. Plan view of the velocity distribution at 1.5 m height

The airflow at this height has a non-uniform and spatially varying distribution across the drift. In the zone between the working face and about 20 m, the velocity field is defined by alternating high and moderate velocity zones. There are localized low-velocity areas, which means that recirculation and low airflow momentum in the breathing zone are at work. The distribution indicates the interaction of the returning airflow of the backflow region with the flow structures that surround it. The velocity distribution at 2.2 m is shown in Figure 15.

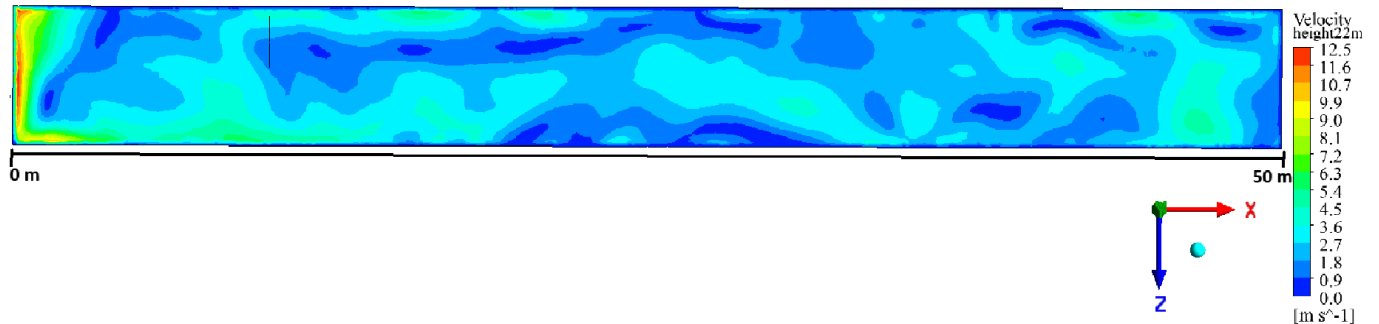


Figure 15. Plan view of the velocity distribution at 2.2 m height

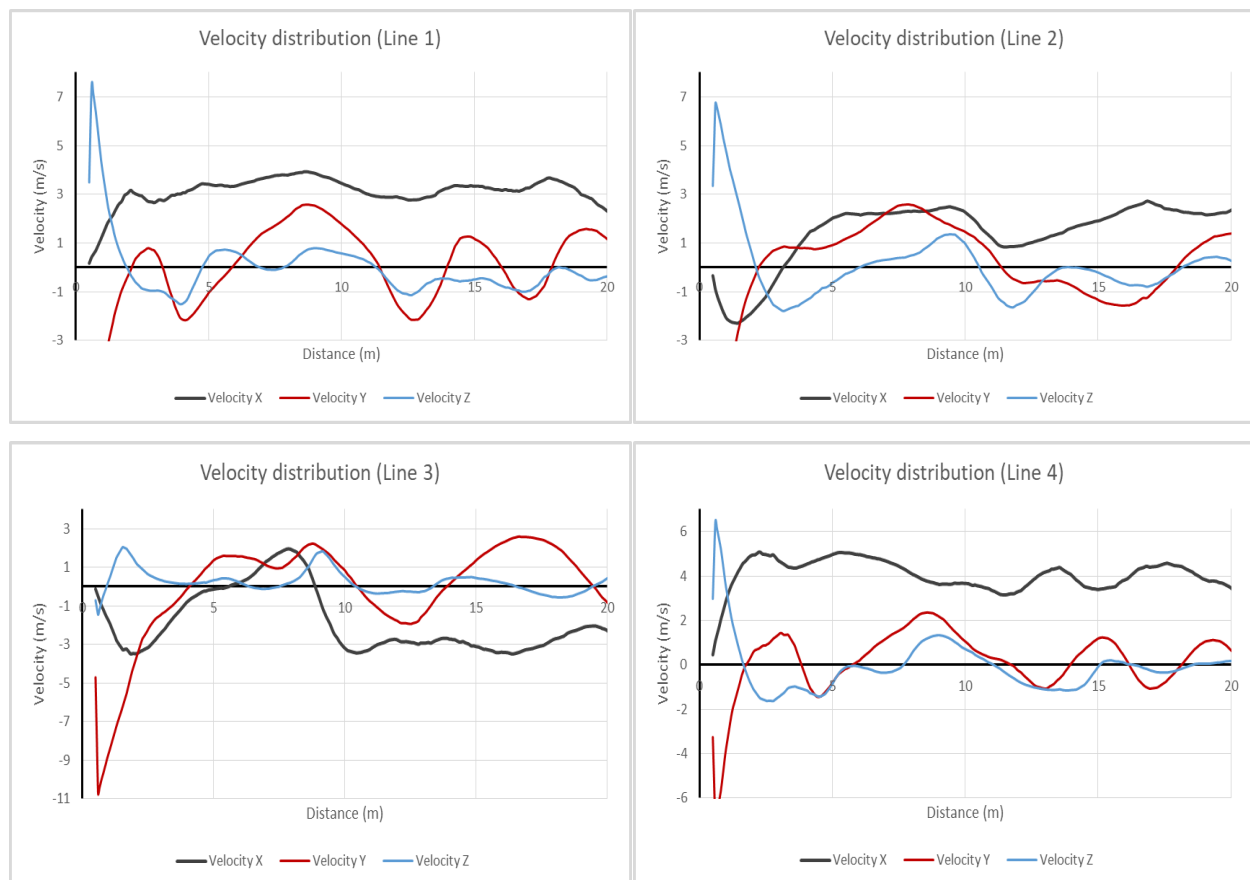
The airflow at this height has a relatively less distributed and stable pattern. Even though the spatial variations do not disappear, the size of the low-velocity areas is more than in the 1.5 m plane. The higher velocity magnitudes are less on the drift, which suggests a less effect of the upper airflow area related to the ventilation ducts and remaining jet momentum. Comparison of the two elevations shows that the airflow in the lower part of the drift maintains greater momentum and is more uniformly distributed, compared to the upper zone which is more influenced by recirculation and local velocity decreases. This vertical change indicates the redistribution of

airflow after the impingement of the jet and the formation of recirculation zones, which affects the airflow characteristics in the tunnel.

4.4 Airflow Velocity Components in X, Y, and Z Directions

The ventilation jet, tunnel geometry and recirculation zones interact to provide the airflow within the drift with a complex three-dimensional behaviour. The airflow velocity components in x, y, and z directions were analyzed at six longitudinal lines at two vertical levels (1.5 m and 2.2 m) and three lateral positions along the drift (Figure 8). This method allows a precise evaluation of the airflow intensity, direction, and stability in the area that is further than the working face.

The velocity components along the six lines are presented in Figure 16. According to the behavior of V_x , V_y and V_z , the airflow in the drift may be separated into two major regions: an unstable flow region in the vicinity of the working face and a developing flow region in the downstream.



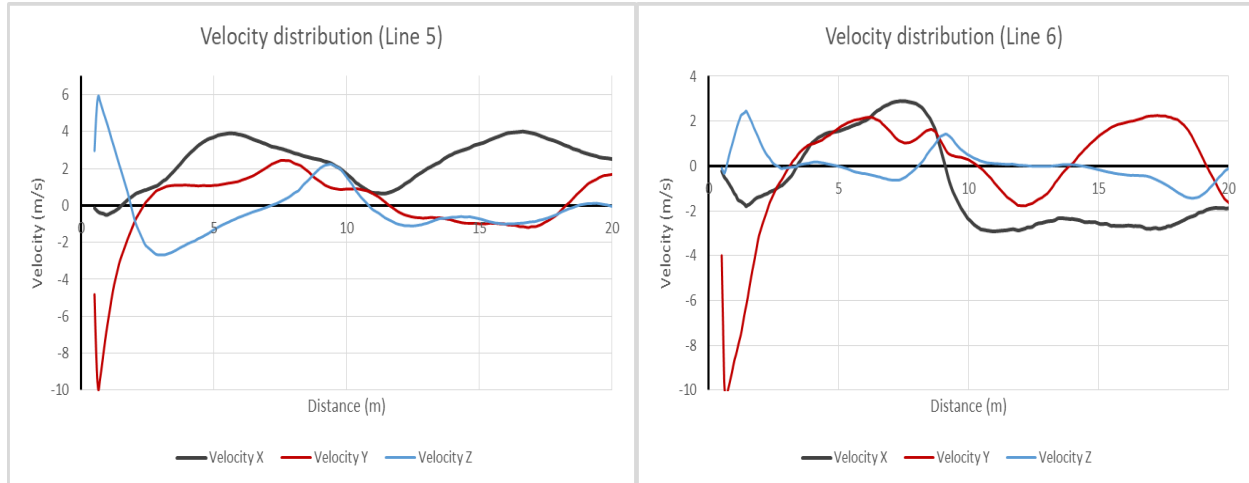


Figure 16. Velocity components (V_x , V_y , V_z) along six longitudinal lines

The airflow in the area near the working face (5 m) is characterized by high variability of all velocity components. Vertical (V_y) and lateral (V_z) components have considerable variations, such as quick changes in magnitude and direction. V_z is higher than 7 m/s in certain places and V_y ranges between about -10 m/s and 2 m/s. These fluctuations suggest very unsteady flow conditions that are caused by jet impingement and the development of strong recirculation areas. The effect of recirculation is still important between 5 m and 10 m, but the airflow starts to restructure. The longitudinal component (V_x) is amplified and more uniform, with a range of 2 m/s to 5 m/s, depending on the position of the line. Nevertheless, V_y and V_z are still oscillating, which indicates the existence of secondary flow structures and constant mixing in the drift. This area is associated with the change of the strongly unstable flow to a more organized flow pattern. Farther downstream, between 10 m and 20 m, the airflow has a more stable and developed behaviour. Longitudinal velocity component (V_x) dominates in most lines with the magnitude of V_y and V_z reducing. Though there are slight variations in the vertical and lateral components, they have less impact on the overall flow structure than in the upstream area. This implies that the intensity of turbulence is gradually decreased and that there is a redistribution of airflow momentum across the drift.

The analysis of the six monitoring lines indicates spatial changes in the airflow behavior. The higher values of V_x at the upper lines (at 2.2 m) are usually more stable, which is due to the effect of the ventilation jet. Conversely, the bottom lines (at 1.5 m) exhibit more intense variations in the vertical (V_y) and lateral (V_z) components, which means that recirculation and backflow

have a greater effect in the breathing zone. Also, there are lateral variations across the drift, whereby the central lines have relatively smoother velocity profiles than the outer areas, where the flow is disturbed by contact with the walls of the tunnel.

4.5 Longitudinal Distribution of Particle Matter

Iso-surfaces of hv vol (heavy volatiles) mass fraction levels (10^{-5} , 10^{-6} , 10^{-7} , and 10^{-8}) were used to analyze the longitudinal distribution of particles in the drift as shown in Fig. 17. These iso-surfaces are the spatial scale of the dispersion of particles on the x-axis of the emission source that is close to the working face ($x \approx 0$ m). The visualization allows the evaluation of the plume propagation, dilution, and persistence under the impact of the ventilation flow field.

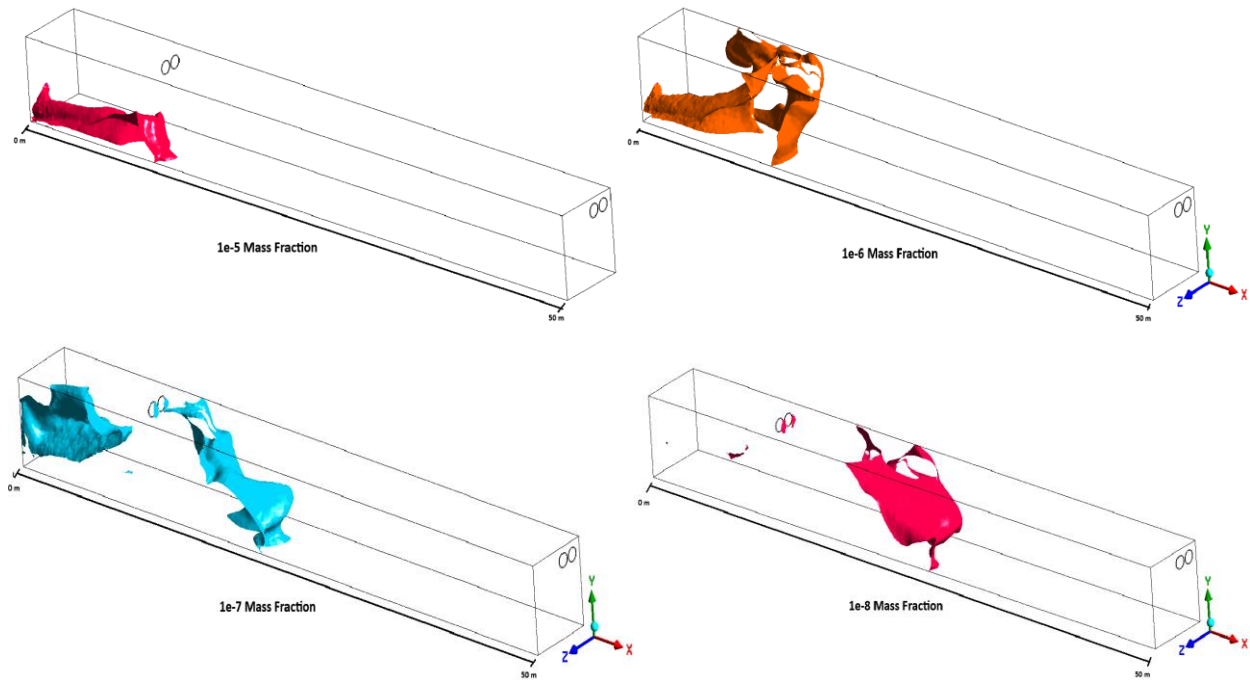


Figure 17. Iso-surfaces of hv_vol mass fraction (10^{-5} - 10^{-8})

At greater levels of concentration (10^{-5}) the particles plume are restricted to the near-source area, with an extension of about 10-12 m downstream. The plume is focused in this area and takes a preferential route along the lower part of the drift, which means that the initial jet momentum prevails and that there is little mixing. The plume spreads further downstream to a

distance of about 12 m as the concentration reduces to 10^{-6} . The iso-surface is widened and distorted, indicating increased turbulent mixing and interaction with the surrounding airflow. The plume is asymmetrically distributed over the drift, which shows the effect of the flow structures caused by ventilation. The distribution of the particles at a concentration level of 10^{-7} is more fragmented. The plume becomes disorganized and discontinuous pockets that reach up to about 20 m. This tendency signifies the shift of jet-dominated transport to turbulence-driven dispersion.

4.6 Cross-Sectional Distribution of Mass Fraction

The analysis of black carbon (BC), represented by the hv_vol (heavy volatiles) mass fraction was conducted using cross-sectional contours at 10 m, 15 m, and 20 m from the working face, which helps in identifying concentration patterns and their relation to the airflow structure. Contours at different monitoring planes are presented in Figures 18-20.

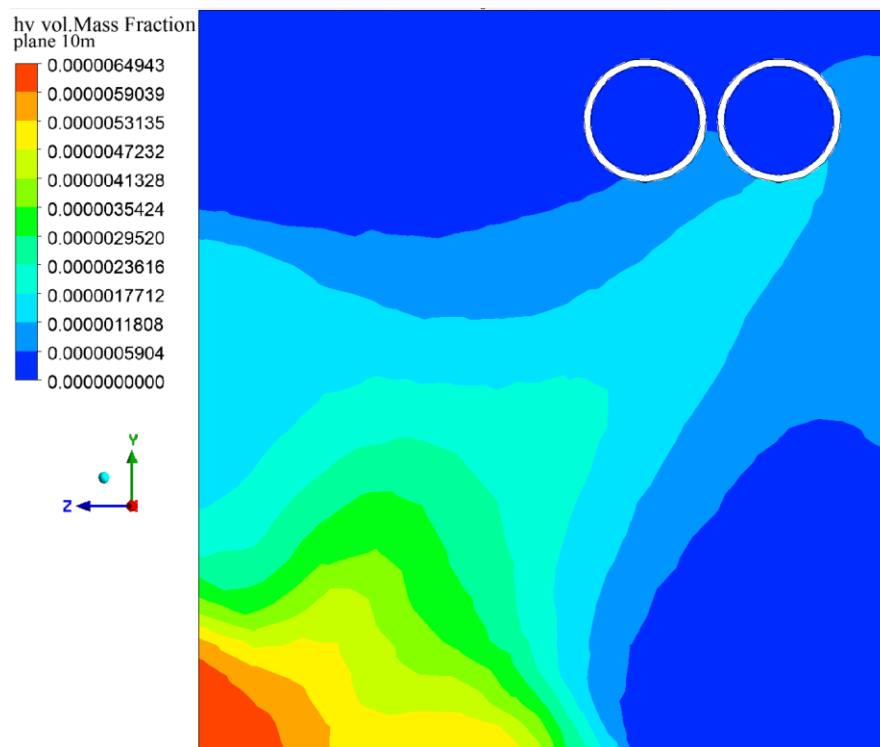


Figure 18. Hv_vol contour at 10 m

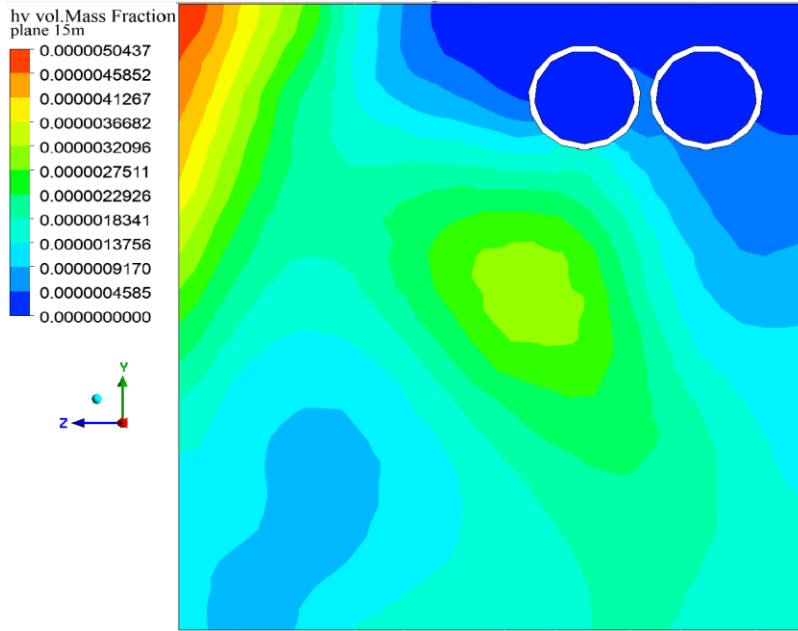


Figure 19. Hv_vol contour at 15 m

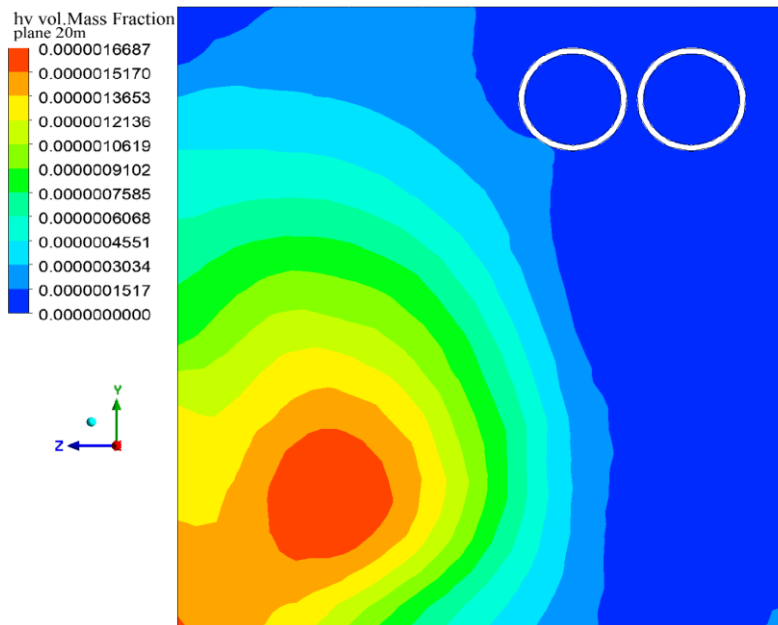


Figure 20. Hv_vol contour at 20 m

The hv_vol mass fraction is very localized at 10 m with an area-weighted average mass fraction of about 3.28×10^{-6} . The distribution shows higher concentrations in the lower-left area of the drift cross-section, with values declining toward the central and right-side areas. This asymmetric distribution indicates that particles are concentrated in the region corresponding to the

recirculation zone identified in the velocity field analysis (Section 4.4). Concentrations are substantially lower on the right side of the drift, particularly around the duct outlets, reflecting the impact of incoming fresh air and local dilution. The hv vol decreases at 15 m, and the average mass fraction decreases to about $2.65 * 10^{-6}$. The spread is more spread out than the 10 m plane, and the area of high concentration spreads to the center of the drift. The less jagged gradients point to a greater mixing and redistribution of particles in the airflow. Although this is spreading, the right side of the drift still exhibits a comparatively low level of concentration, which proves the ongoing influence of ventilation. The hv_vol is further decreased at 20 m with the average mass fraction of about $9.12 * 10^{-7}$. The distribution is more evenly spread across the cross-section, and gradual concentration gradients show further mixing and dilution. The region of higher concentration moves towards the central-lower part of the drift, and the right part, particularly around the ducts, has a constant lower value.

Zone Classification Framework:

- **Zone A (High/Medium-High Hazard):** Areas with elevated mass fraction, corresponding to red and orange colored regions in Figures 18-20.
- **Zone B (Medium Hazard):** Areas with moderate mass fraction, corresponding to yellow and green colored regions.
- **Zone C (Low Hazard):** Areas with minimal mass fraction, corresponding to blue colored regions.

1) Hazard Zones at 10 m Plane

At 10 m, Zone A (red/orange region, Figure 18) occupies the lower-left area of the drift cross-section with mass fraction values of $3.28-6.4 * 10^{-6}$. This zone occupies approximately 15-20% of the drift cross-section. Peak values occur at monitoring points #4 and #1 (lower-left region at breathing height 1.5 m and upper region 2.2 m respectively). Zone B (yellow/green region, Figure 18) occupies the central area with mass fraction values of $1.5-3.0 * 10^{-6}$. This zone represents approximately 35-40% of the cross-section.

Zone C (blue region, Figure 18) occupies the right side of the drift with mass fraction values below $0.5 * 10^{-6}$. This zone comprises approximately 35-45% of the cross-section.

2) Hazard Zones at 15 m Plane

At 15 m, Zone A (red/orange-yellow region, Figure 19) is located in the center-left area with mass fraction values of $2.65-4.5 * 10^{-6}$. This zone occupies approximately 20-25% of the cross-section.

The lateral location of the highest concentrations has shifted from the left wall (at 10 m) toward the center (at 15 m). Zone B (green region, Figure 19) comprises 40-45% of the cross-section with mass fraction values of $1.0\text{-}2.5 * 10^{-6}$. Zone C (blue region, Figure 19) comprises 30-40% of the cross-section with lower concentrations.

3) Hazard Zones at 20 m Plane

At 20 m, Zone A (red/orange-yellow region, Figure 20) is located in the lower-left area with mass fraction values of $1.0\text{-}1.6 * 10^{-6}$. This zone occupies approximately 15-20% of the cross-section. Zone B (green region, Figure 20) comprises 35-45% of the cross-section with mass fraction values of $0.5 * 10^{-7}\text{-}1.0 * 10^{-6}$. Zone C (blue region, Figure 20) comprises 35-45% of the cross-section with mass fraction values below $0.3 * 10^{-7}$.

4.7 Black Carbon (BC) and LDSA analysis

To provide a more practical interpretation of the results, the normalized mass fraction values of $h\nu_{vol}$ were converted into equivalent black carbon (BC) concentrations. This conversion was performed using the relation: $C_{BC} = Y_{h\nu-vol} * \rho_{air} * 10^9$, where Y represents the mass fraction and ρ is the air density. The resulting values were expressed in $\mu\text{g}/\text{m}^3$ to allow comparison with reported data from underground mining environments. Furthermore, the lung-deposited surface area (LDSA) was estimated from the calculated BC concentrations using an empirical relationship given by equation (10). This association allows the evaluation of possible health hazards of exposure to ultrafine particles on the basis of the concentration data.

Table 1 shows the BC levels and the values of LDSA at the selected monitoring points on the three planes (10 m, 15 m, and 20 m). Red data indicate the highest concentrations (Zone A), yellow data indicate the mean (Zone B) and green data indicate the lowest concentrations (Zone C).

Table 1. Black carbon concentration ($\mu\text{g}/\text{m}^3$) and lung-deposited surface area ($\mu\text{m}^2/\text{cm}^3$) at selected monitoring points for planes at 10 m, 15 m, and 20 m

	Plane 10m		
Name	#1 point	#2 point	#3 point
Hv_vol (Mass Fraction)	3.16E-06	1.97E-06	1.17E-06
BC ($\mu\text{g}/\text{m}^3$)	3866	2417	1437
LDSA ($\mu\text{m}^2/\text{cm}^3$)	6891	3992	2032
	#4 point	#5 point	#6 point
Hv_vol (Mass Fraction)	3.59E-06	2.85E-06	1.55E-06
BC ($\mu\text{g}/\text{m}^3$)	4404	3490	1898
LDSA ($\mu\text{m}^2/\text{cm}^3$)	7966	6138	2953
	Plane 15m		
Name	#1 point	#2 point	#3 point
Hv_vol (Mass Fraction)	1.30E-06	2.77E-06	2.22E-06
BC ($\mu\text{g}/\text{m}^3$)	1596	3396	2718
LDSA ($\mu\text{m}^2/\text{cm}^3$)	2349	5950	4595
	#4 point	#5 point	#6 point
Hv_vol (Mass Fraction)	1.20E-06	2.55E-06	2.25E-06
BC ($\mu\text{g}/\text{m}^3$)	1469	3123	2752
LDSA ($\mu\text{m}^2/\text{cm}^3$)	2095	5404	4662
	Plane 20m		
Name	#1 point	#2 point	#3 point
Hv_vol (Mass Fraction)	1.52E-06	9.47E-07	6.72E-07
BC ($\mu\text{g}/\text{m}^3$)	1866	1160	823
LDSA ($\mu\text{m}^2/\text{cm}^3$)	2891	1479	803
	#4 point	#5 point	#6 point
Hv_vol (Mass Fraction)	1.69E-06	1.00E-06	6.95E-07
BC ($\mu\text{g}/\text{m}^3$)	2076	1225	851
LDSA ($\mu\text{m}^2/\text{cm}^3$)	3310	1608	860

The maximum BC concentrations were found at 10 m with a maximum of $4,404 \mu\text{g}/\text{m}^3$, which is equivalent to LDSA values of $7,966 \mu\text{m}^2/\text{cm}^3$. This means that there is a high level of pollutant build-up and high exposure potential in the source and vortex area. At 15 m, the BC concentrations decrease to a range of $1,469 \mu\text{g}/\text{m}^3$ to $3,396 \mu\text{g}/\text{m}^3$, resulting in LDSA values

between $2,095 \mu\text{m}^2/\text{cm}^3$ and $5,950 \mu\text{m}^2/\text{cm}^3$. This is why the mixing and partial dilution of the pollutant plume increases with distance down the stream moving the high-risk zone to the right of the left wall and the center of the drift. Further decrease in the concentration of BC is noted at 20 m with values of $823 \mu\text{g}/\text{m}^3$ to $2,076 \mu\text{g}/\text{m}^3$, which correspond to LDSA of $803 \mu\text{m}^2/\text{cm}^3$ to $3310 \mu\text{m}^2/\text{cm}^3$. This trend is further confirmed by the averaged concentrations across each plane. At 10 m, the average BC concentration is approximately $2,920 \mu\text{g}/\text{m}^3$, corresponding to an average LDSA of $5,000 \mu\text{m}^2/\text{cm}^3$, representing the highest overall exposure level. At 15 m, the average BC decreases to approximately $2,510 \mu\text{g}/\text{m}^3$ with an LDSA of $4,180 \mu\text{m}^2/\text{cm}^3$, indicating moderate reduction due to mixing. At 20 m, a substantial decrease is observed, with average BC concentration dropping to $1,330 \mu\text{g}/\text{m}^3$ and LDSA to $1,830 \mu\text{m}^2/\text{cm}^3$. This consistent decline in both peak and average values confirms that pollutant concentrations are progressively reduced along the drift due to ventilation effects, while still maintaining localized spatial variability. It is worth noting that both the BC and LDSA values are based on normalized tracer simulations and hence indicative. Nevertheless, they offer a solid foundation of comparative analysis and evaluation of relative exposure in the drift.

To measure the change in the distribution of the pollutants along the drift, the percentage change in the concentration of black carbon (BC) and the lung-deposited surface area (LDSA) at the 10 m, 15 m and 20 m planes was assessed. Table 2 summarizes the results.

Table 2. Percentage variation of BC and LDSA between the 10 m and 15 m planes

	#1 point	#2 point	#3 point
BC ($\mu\text{g}/\text{m}^3$)	-142%	29%	47%
LDSA ($\mu\text{m}^2/\text{cm}^3$)	-193%	33%	56%
	#4 point	#5 point	#6 point
BC ($\mu\text{g}/\text{m}^3$)	-200%	-12%	31%
LDSA ($\mu\text{m}^2/\text{cm}^3$)	-280%	-14%	37%

Table 3. Percentage variation of BC and LDSA between the 15 m and 20 m planes

	#1 point	#2 point	#3 point
BC ($\mu\text{g}/\text{m}^3$)	14%	-193%	-230%
LDSA ($\mu\text{m}^2/\text{cm}^3$)	19%	-302%	-472%
	#4 point	#5 point	#6 point
BC ($\mu\text{g}/\text{m}^3$)	29%	-155%	-223%
LDSA ($\mu\text{m}^2/\text{cm}^3$)	37%	-236%	-442%

The overall change in black carbon (BC) concentration and lung-deposited surface area (LDSA) between different monitoring planes was evaluated to quantify the rate of pollutant along the drift. The percentage change was calculated based on the average values across the monitoring points using the following relation:

$$\% \Delta = \frac{\bar{C}(2) - \bar{C}(1)}{\bar{C}(1)} * 100 \quad (11)$$

Where, $\bar{C}(1)$ and $\bar{C}(2)$ represent the average concentrations at two consecutive planes. Between 10 m and 15 m, a moderate decrease in concentration was observed, with BC -14% and LDSA -16%. This indicates partial dilution of the pollutant plume while maintaining relatively elevated concentration levels due to ongoing recirculation and mixing. Major reduction was observed between 15 m and 20 m, where concentration changes showed BC -47% and LDSA -56%.

5. DISCUSSION

The primary aim of this study is to determine the spatial distribution of lung-deposited surface area (LDSA) in a mechanically ventilated mine drift and to identify hazard zones of elevated respiratory exposure. Because LDSA was estimated from black carbon (BC)

concentration via: $LDSA = (BC - 421)/0.50$ (Sabanov et al., 2025), and BC was derived from the hv_vol mass fraction field simulated by the CFD model, the spatial pattern of LDSA is fundamentally governed by the mass fraction distribution. The hv_vol mass fraction is the primary scalar variable solved in the CFD model, governing diesel particulate transport through convection and turbulent diffusion; all BC and LDSA values are linear post-processing transformations of this field. The spatial structure of LDSA hazard zones is therefore determined by the mechanisms controlling the mass fraction: jet dynamics, recirculation, and the transition to ventilation-dominated transport.

Within the first 10 m of the drift, diesel particulate confinement is primarily governed by jet recirculation. The high-velocity ventilation jet (30 m/s) impinges upon the working face and redirects downward, establishing a backflow zone that severely limits downstream mass fraction dispersion. At the 10 m plane, the area-weighted average hv_vol mass fraction reaches $3.28 * 10^{-6}$, with peak values concentrated in the lower-left region of the cross-section. After conversion, this yields a peak BC concentration of $4,404 \mu g/m^3$ and a peak LDSA of $7,966 \mu m^2/cm^3$ the highest values in this study, localised at monitoring points #4 and #1. The persistence of this elevated LDSA is explained by strong fluctuations in vertical (V_y : -10 to +2 m/s) and lateral (V_z : ± 7 m/s) velocity components while the longitudinal component (V_x) remains weak; these conditions prevent efficient downstream advection of the mass fraction. Vertically, the breathing zone at 1.5 m contains localized near-stagnation pockets (Figure 14) that further allow mass fraction to accumulate, producing higher LDSA values at breathing height than at 2.2 m at the same horizontal position a height-dependent heterogeneity that conventional single-point monitoring may fail to capture. Between 10 m and 15 m, the average mass fraction decreases from $3.28 * 10^{-6}$ to $2.65 * 10^{-6}$, yielding LDSA values of 2,095-5,950 $\mu m^2/cm^3$ (a 16% mean reduction). The velocity field transitions from strongly asymmetric (Figure 11) to more centralised (Figure 12), with V_x gaining dominance while V_y and V_z diminish, partially disrupting recirculation-driven accumulation and allowing turbulent mixing to redistribute the mass fraction plume from the lower-left region toward the center of the drift. The respiratory hazard in this zone is therefore spatially redistributed rather than eliminated, representing a transitional exposure regime consistent with established understanding of turbulent mixing in confined ventilated environments (Leristö et al., 2022). Between 15 m and 20 m, ventilation becomes the dominant

mechanism: the average mass fraction falls to 9.12×10^{-7} , yielding LDSA values of 803-3,310 $\mu\text{m}^2/\text{cm}^3$ with a 56% mean reduction. The longitudinal component (V_x : typically 5-10 m/s) dominates with only minor V_y and V_z oscillations, providing efficient axial advection and producing a smoother, more homogeneous LDSA distribution. The non-linear ventilation effectiveness -16% LDSA reduction per 5 m near the source versus -56% per 5 m in the far field, demonstrates that a characteristic transition occurs at approximately 15 m, beyond which developed flow conditions enable substantially more efficient dilution of the LDSA hazard, consistent with findings on fully developed airflow in underground ventilation systems (Salo et al.).

Taken together, the LDSA hazard is structured into three spatially distinct zones: a high-LDSA recirculation-dominated zone (10 m), a transitional zone (10-15 m) with partial redistribution, and a lower-LDSA ventilation-dominated zone (15-20 m). Based on the mass fraction distribution and corresponding LDSA values, these regions can be further classified into a hazard mapping framework consisting of three categories: Zone A (high hazard), Zone B (medium hazard), and Zone C (low hazard). This classification is supported both by the contour patterns observed in Figures 18-20 and by the quantitative values presented in Table 1, where higher mass fraction and LDSA concentrations consistently correspond to Zone A (red), intermediate values to Zone B (yellow), and lower values to Zone C (green). At 10 m, the region is predominantly classified as Zone A (high hazard), particularly near the left wall where LDSA reaches 6,891-7,966 $\mu\text{m}^2/\text{cm}^3$ (points #1 and #4). Central regions fall within Zone B (medium hazard), with LDSA values of 3,992-6,138 $\mu\text{m}^2/\text{cm}^3$ (points #2 and #5), while the right wall approaches the lower bound of Zone B transitioning toward Zone C, with values between 2,032-2,953 $\mu\text{m}^2/\text{cm}^3$ (points #3 and #6). This distribution reflects recirculation-driven accumulation of pollutant mass fraction on the left side, with left-wall LDSA approximately 2.7-3.4 times higher than at the right wall. At 15 m, the hazard distribution shifts spatially. The left wall transitions to Zone C (low hazard), with LDSA decreasing significantly to 2,095-2,349 $\mu\text{m}^2/\text{cm}^3$ (a 66–70% reduction from 10 m). In contrast, the central and right regions transition into Zone A-B, with LDSA values increasing to 4,595-5,950 $\mu\text{m}^2/\text{cm}^3$. This indicates lateral redistribution of pollutants due to turbulent mixing. Importantly, the hazard does not diminish but relocates, meaning that exposure risk becomes concentrated in the central flow region rather than near the

wall. At 20 m, ventilation-driven dilution results in a predominance of Zone C (low hazard) conditions, particularly at the right wall where LDSA reaches the lowest values of the study (803-860 $\mu\text{m}^2/\text{cm}^3$). However, a residual Zone B (medium hazard) persists near the left wall (2,891-3,310 $\mu\text{m}^2/\text{cm}^3$), likely associated with weaker downstream recirculation structures identified in the velocity field. These lateral and vertical sub-patterns confirm that exposure risk is highly position-specific within each zone and cannot be adequately represented by cross-sectional averaged measurements.

Because LDSA declines by only 16% between 10 m and 15 m but by 56% between 15 m and 20 m, exposure control efforts targeting recirculation suppression near the working face, such as modified jet trajectory, secondary jets to disrupt vortex formation, or source-capture ventilation are expected to yield greater reductions in peak LDSA than far-field dilution improvements. Source-capture ventilation is likely the most effective intervention, although duct configuration modifications may offer more practical implementation in operating mines. These findings are consistent with previous studies highlighting the importance of airflow control and ventilation design in minimizing pollutant accumulation in underground mining environments (Salo et al.).

Several limitations affect the quantitative interpretation of LDSA values. The steady-state modelling assumption does not capture transient variations in engine load or ventilation; peak LDSA during high-load cycles may exceed predicted values, although the three-zone spatial structure is expected to persist. The passive scalar treatment of DPM neglects deposition and agglomeration, likely providing a conservative (high-side) LDSA estimate. Simplified tunnel geometry omits equipment and infrastructure, which may underestimate fine-scale flow complexity while preserving dominant jet-recirculation structures. Most critically, LDSA was derived from an empirical relationship rather than directly simulated, due to ANSYS software limitations, and its applicability to the specific emission characteristics of the modelled LHD has not been independently validated; field validation through simultaneous BC and direct LDSA measurement is required for complete quantitative health risk assessment. Despite these limitations, the relative spatial pattern of LDSA three distinct hazard zones, peak LDSA localized in the recirculation zone at breathing height, non-linear ventilation effectiveness, and lateral plume migration at 15 m are expected to be robust features of auxiliary ventilation systems with similar geometry and operating conditions.

6. CONCLUSION

The aim of this study was to analyze the spatial distribution of lung-deposited surface area (LDSA) concentrations in a mechanically ventilated underground mine drift and to determine hazard zones of elevated respiratory exposure from diesel particulate matter (DPM). To achieve this, a CFD model was developed to simulate airflow and scalar pollutant transport, with DPM represented as a passive scalar mass fraction (hv_vol). The mass fraction field was subsequently converted to black carbon (BC) concentration and then to LDSA using an empirical relationship. The central outcomes of the modelling are as follows;

Three distinct LDSA hazard zones were determined within the drift. The recirculation-dominated zone (0-10 m) constitutes the primary hazard zone, where jet impingement on the working face creates a backflow region that traps the scalar mass fraction and produces peak LDSA values of up to $7,966 \mu\text{m}^2/\text{cm}^3$ at specific monitoring locations in the lower-left quadrant at breathing height (1.5 m). This zone represents the highest respiratory exposure risk, and workers conducting sustained tasks here are not recommended to remain in the recirculation area without adequate personal protective equipment or engineering controls. The transitional zone (10-15 m) is a moderate-hazard zone with LDSA values of $2,095\text{--}5,950 \mu\text{m}^2/\text{cm}^3$, where turbulent mixing redistributes but does not eliminate the LDSA hazard. The ventilation-dominated zone (15-20 m) is a lower-hazard zone with LDSA values of $803\text{--}3,310 \mu\text{m}^2/\text{cm}^3$, where developed longitudinal flow substantially reduces the mass fraction and therefore the LDSA exposure.

The non-linear spatial decay of LDSA is a key finding of the modelling. LDSA decreased by 16% between the recirculation zone (10 m) and the transition zone (15 m), but by 56% between the transition zone (15 m) and the ventilation-dominated zone (20 m). This asymmetry identifies a characteristic distance of approximately 15 m beyond which ventilation efficiency substantially increases, and demonstrates that engineering controls targeting recirculation suppression near the working face will produce greater reductions in LDSA at the most hazardous locations than equivalent improvements directed at far-field dilution.

Height-dependent LDSA heterogeneity was identified at all three monitoring planes. The breathing zone (1.5 m height) consistently exhibited higher LDSA values than the upper region (2.2 m) at equivalent horizontal distances, because the near-stagnation velocity conditions at 1.5

m allow greater mass fraction accumulation. This finding demonstrates that exposure assessment conducted at arbitrary heights or using cross-sectional averages will underestimate the LDSA dose received by workers in the near-face recirculation zone.

This study makes three contributions to occupational exposure assessment in underground mines. Methodologically, it demonstrates that CFD-based spatial mapping can determine LDSA hazard zones with spatial resolution unavailable to conventional point measurements, and that the mass fraction field provides the physical basis for quantifying the LDSA distribution. Empirically, it provides quantitative evidence that LDSA reduction is non-linear with distance and that the highest hazard is localized at specific positions within the recirculation zone rather than being uniformly distributed. Conceptually, it demonstrates that location-specific and height-specific LDSA assessment is necessary for accurate hazard determination in spatially heterogeneous ventilation systems, a requirement that cannot be met by time-integrated, location-averaged measurements alone.

Future research should prioritize: (1) field validation of the BC-LDSA relationship through simultaneous portable measurement of BC and direct LDSA within each of the three spatial zones identified, conducted specifically at breathing height (1.5 m); (2) transient CFD modelling to determine whether steady-state results represent worst-case or typical-case LDSA exposure conditions across operational duty cycles; (3) particle dynamics modelling including deposition and agglomeration to assess whether the passive scalar assumption produces conservative LDSA estimates; and (4) CFD evaluation of alternative ventilation configurations including modified jet trajectories and source-capture systems, to identify designs capable of suppressing the recirculation-driven LDSA hazard zone near the working face.

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