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DPM simulation in an underground entry: Comparison between particle and species models

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ABSTRACT

The diesel particulate matter (DPM) emission from diesel powered equipment in underground mines can cause health hazards including cancer to the miners. The understanding of the DPM propagation pattern under realistic mining condition is required for selecting proper DPM control strategies and to improve working practices in underground mines. In this paper, three dimensional simulations of DPM emission from the exhaust tail pipe of a load-haul-dump (LHD) vehicle and its subsequent distribution inside an isolated zone in the typical underground mine are carried out using two different solution models available in Ansys Fluent. The incoming fresh air into the isolated zone is treated as a continuous phase and DPM is treated either as a continuous phase (gas) or as a secondary discrete phase (particle). Species transport model is used when DPM is treated as gas and discrete phase model is used when DPM is assumed to behave like a particle. The distributions of DPM concentration inside the isolated zone obtained from each method are presented and compared. From the comparison results, an accurate and economical solution technique for DPM evaluation can be selected.

1. Introduction

Diesel engine operated LHDs and trucks are widely used in underground metal/non-metal mines. Although they have better fuel efficiency, emission from the tail pipe and its subsequent distribution in the underground mine are of growing concern for miners. DPM is the particulate byproduct of diesel exhaust and it can exist in different modes with different size distributions (5 nm–10 μm). 90% of the DPM emitted from the diesel engines have size distributions in nanometer ranges. Due to its very small size, it will remain airborne for long duration of time and pollutes the entire mine environment causing health hazard to the miners. It is established that long time exposure to diesel exhaust can lead to cancer, asthma and other health effects such as eye and nose irritation, headaches and nausea [1–6].

Many researchers have carried out both experimental and numerical studies on diesel particle matter emission. For example, Kim et al. studied formation of DPM inside the turbulent exhaust plume of a diesel vehicle [7]. They used Ansys Fluent computational fluid dynamics (CFD) code to determine the formation of diesel particulates by nucleation and coagulation. Uhrner et al. studied the turbulent diffusion of plume exhaust from the diesel engine using both experimental and numerical approach [8]. Another interesting study on the deposition of ultra-fine particles from diesel exhaust aerosol was carried by Desantes et al. [9]. Henrik Strom and Bengt Andersson performed Eulerian–Lagrangian CFD modeling to simulate trapping of diesel and gasoline particulate matter in flow-through devices [10]. They used eight different types of diesel and gasoline particulate matter (different densities) in their simulation. Although all these studies are related to the diesel particulate matter, these are not related to the mine environment.

In the underground environment, Ray et al. studied NO_2 distribution for underground passenger railroad tunnel utilizing diesel locomotives [11]. CFD was used to evaluate the effectiveness of natural and mechanical ventilation system. Simulation of DPM dispersion in underground metal/nonmetal mines was carried out by Zheng and Tien [12]. In this study, the DPM was considered to behave like a gas and not as particle. The treatment of DPM as a gas was later incorporated the buoyancy effect and compared with a test, in which the simulation agreed with the test at a practical accuracy [13,14]. Kurnia et al. studied a diesel powered continuous miner and shuttle car face with CFD to simulate the distribution of hazardous gases and optimize the local ventilation system [15].

In other mining studies, CFD simulations have been used in mining research to detect spontaneous combustion and apply

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inertization in gob areas, study airflow patterns and gas concentrations in continuous miner face ventilation configurations, investigate scrubber intake designs and water mist flow for longwall dust control, and estimate a mine's ventilation status after a disaster [16–25].

The present study focuses on the diesel particulate emission and its diffusion inside the underground mine areas. To the author's knowledge, the study of DPM inside the underground metal/non-metal mines assuming DPM to behave like a particle than as a gas was not considered and that motivated the present study. In this paper, a region of an isolated zone at Noranda Inc.-Brunswick Mine was selected to conduct a CFD study to determine the DPM distribution pattern and to identify locations with high DPM concentration [26]. The CFD study was conducted using both discrete phase model and species transport model available in Fluent. The comparison between these models is made and the results are presented in this study.

2. Diesel emission evaluation program (DEEP)

The objective of the DEEP field study conducted in an isolated zone at Noranda Brunswick Mine was to investigate the effectiveness of the diesel particulate filter (DPF) in the underground mine environment [26]. They selected LHD vehicles and haulage trucks fitted with DPF filters to do the study. The section of drift is about 400 m long and the vehicles were operated inside this 400 m zone by repeating an 8 min production cycle. The layout for this isolated zone along with the locations of the three DPM sampling stations is shown in Fig. 1. From this study, the average carbon concentration at the exhaust sampling station were obtained for different vehicles and the results are shown in Fig. 2. The configuration of this isolated zone along with the measured results from this study will be used in the present CFD analysis to predict the DPM distribution and to identify the regions that exceeds the current regulatory requirement for DPM concentration (>160 μg/m^3) in this isolated zone.

3. Problem statement

A portion of the isolated zone shown in Fig. 1 (approximately 134 m) with one dead-end is selected for the present computational study. An LHD vehicle is placed inside this single entry with its tail pipe emission against the direction as that of the fresh air flow. Three-dimensional turbulent simulation of diesel particulate matter is carried out and a schematic of the computational domain is shown in Fig. 3. The length of the single entry (L) measures approximately 134 m. The height (H) and width (W) are 4.8 and 4.0 m respectively at the inlet. The physical properties of fresh air flow are treated as constants and evaluated for inlet temperature of $T_0 = 27$ °C (i.e., specific heat (C_p) is 1006 J/(kg K), dynamic viscosity (μ) is 1.789×10^{-5} kg/(m s), and thermal conductivity (k) equals to 0.0242 W/(m K)).

The density variation in the fluid due to temperature gradient that exists between the air intake temperature and the tailpipe emission temperature is calculated using the incompressible ideal gas model available in Fluent. In this model, the flow is assumed to be incompressible but density change due to temperature is calculated using ideal gas law. In the presence of gravity, this density gradient results in buoyancy flow. Numerical simulation of DPM distribution inside the single entry is performed using the discrete phase model and species transport model available in Fluent.

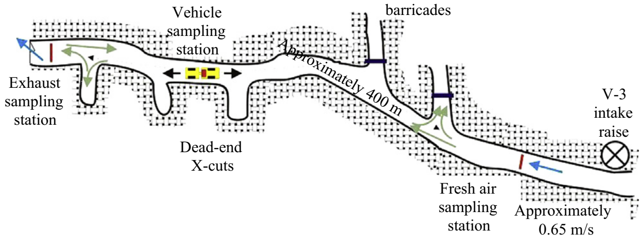

Fig. 1. Isolated zone layout in DEEP field study [26].

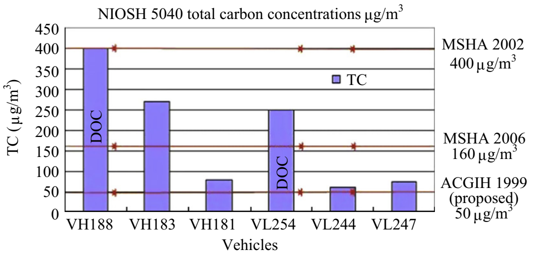

Fig. 2. Total carbon concentrations at the exhaust sampling station [26].

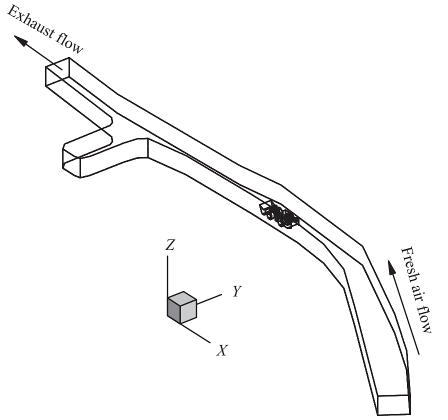

Fig. 3. Schematic of the single entry with one dead-end.

In the discrete phase model, particles are assumed to be of inert type and having constant diameter $d_p = 70$ nm. The physical properties of the particle are treated as constants with density ($\rho_d = 1000$ kg/m^3), specific heat ($C_p = 1220$ J/(kg K)) and thermal conductivity ($k = 0.0242$ W/(m K)). The thermal conductivity of particles is assumed to be equal to that of air (i.e. $k_p = k_{air}$). This is due to the reduced heat conductivity of nano-sized particles [27]. In the present study, two-way coupling (the interaction of the gas phase with particles and vice versa) is considered. So the particles can exchange heat and momentum with continuous phase (air). The limitation in this model is that particle–particle interaction is neglected. The DPM from the tail pipe of LHD is injected into the simulation domain using surface injection option available in discrete phase model of Fluent. The DPM is injected into the computational domain for every fluid flow (continuous phase) time step. The tailpipe boundary surface is made up of 44 cell faces. In surface injection, one particle packet is released from each cell face and overall 44 particle packets from the tailpipe surface for each time step. Each particle packet will contain millions of individual particles and the discrete phase tracks the particle packets rather than millions of individual particles since it is practically impossible to track them computationally [28]. The number of individual particles in each packet will vary depending on the time step used to satisfy the DPM mass flow rate requirements.

In the species transport model, DPM is treated as gas (continuous phase) and the material that is selected as a representative for the DPM is n-octane vapor (C_8H_{18}) with density ($\rho = 4.84$ kg/m^3),