Integrated Numerical Simulation on Gas Diffusion in Mine Ventilation Network

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ABSTRACT: The Discrete Tracer Points Method (hereinafter DTPM), a Lagrangian based random walk method by making moves of imaginary points in flow regions, has been developed in this study. This method considers turbulent velocity profile, velocity fluctuations, Reynolds stress and turbulent flow intensities. The results have shown good consistency compared to other experimental and analytical results for single and straight channel flows. In order to simulate gas or dust diffusion in mine ventilation network flows, a scheme to treat the flow separation at junctions has been also developed. Furthermore, various dead spaces connected with mine ventilation airways has been modeled by considering extended region of the airways to simulate the retaining effect due to trapped gas/dust in dead spaces. In this paper, a new calculation model has been presented based on dead space ratio to induce decay time of points located in various dead spaces to get matching with experimental results by laboratory experiments using tracer gas and a rectangular cavity model constructed in an open-loop wind tunnel. Furthermore, the tracer gas measurements in the mine ventilation network flow at Kushiro Coal Mine were carried out and simulated numerically by DTPM extended by the new calculation model inducing time decay in dead spaces. The good matching simulation results have been obtained by setting dead space ratio, ψ=35% for the ventilation network. It is concluded that DTPM is a useful tool for better understanding turbulent diffusion phenomena in mine ventilation network, and it can provide easy numerical visualization since this method allows tracking record of each point, such as position at certain time and its travelling paths.

1 INTRODUCTION

The dispersion mechanism holds an important role in control gasses or particulates spreading from its source throughout underground mine ventilation. Thus, certain measurement and simulation methods are required to investigate their effects on mine environment and safety operations. Yet, only few studies have been aimed at evaluating the turbulent diffusion occurred in mine airways.

Authors have developed the numerical ventilation simulator "MIVENA" (see Sasaki & Dindiwe, 2002), and Grenier et al. (1992), Widodo et al. (2008) and Widiatomojo et al. (2013a) have carried studies on turbulent gas diffusion phenomena using tracer gas method. These studies involved numerical investigation of effective diffusion coefficient based on one-dimensional advection-diffusion equation. These results showed relatively high value of effective diffusion coefficients and long trailing effect observed in the measured curves. These studies pointed out that the recirculation flow in cavities existing in mine airway-networks may contribute on these.

Further detailed numerical approaches, e.g. three-dimensional numerical model, are required to simulate the turbulent dispersion mechanism. Three-dimensional numerical simulation, such as Computational Fluids Mechanics (CFD) is very useful tool to understand airflow characteristics, but not perfect for all kind of diffusions in turbulent airflows, because CFD also stands on some assumptions or models to calculate vortex diffusion and dissipation. Therefore, CFD may be applied for flow simulations limited flow domains, and it is not suitable to carry out flow simulations targeting all airways in the mine ventilation network.

The Discrete Tracer Point Method (DTPM), a Lagrangian based random walk method, is presented in this study. The diffused gas is treated as imaginary points and move based on velocity profiles, turbulent intensities, Reynolds stress and turbulent stochastic process. The DTPM need a scheme to treat network flow. It must be simple and can be incorporated with the network data provided from mine-ventilation simulators. In addition, a laboratory experiment in a wind tunnel was also carried out to investigate the delay time of gas or dusts in cavities that are used to be observed along mine airways.

The aims of this study are to present a new calculation model to treat delay time in dead spaces that characterizes turbulent diffusion phenomena from inlets to exhausts in mine ventilation network. The integrated numerical simulation method has been successfully applied for tracer gas diffusion in an operated mine ventilation network, and the reason of high effective diffusion coefficients observed in mine ventilations has been explained by recirculation flows in various dead spaces.

Figure 1 illustrates the tracer gas measurement in mine ventilation network and the possible recirculation flows in dead spaces, such as cavities.

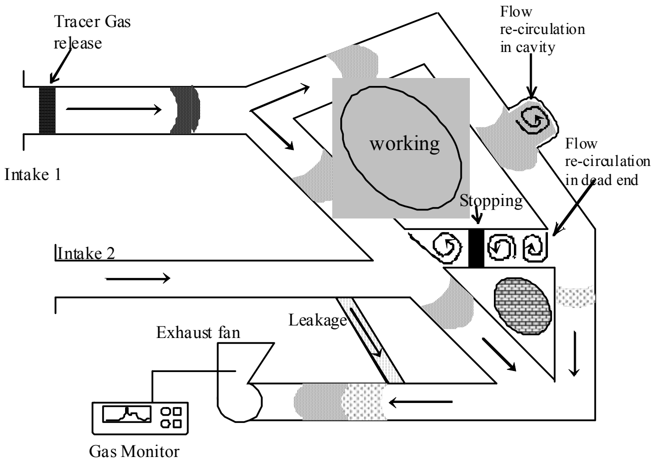


Figure 1. Illustration of tracer gas measurement in underground mine ventilation network

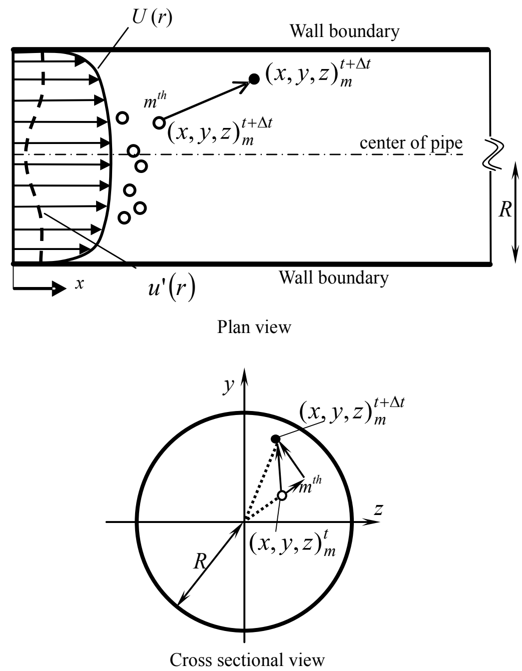
2 NUMERICAL SIMULATUON SCHEME

The DTPM is completely different from methods of directly solving partial differential equations. DTPM has several advantages such that no grid generation required. This method calculates points' location in the space and time domains instead of direct calculation of mass transfer based on its concentration gradient. Therefore, DTPM calculation time can be minimized by automatic satisfying mass valance. The calculated result of points' displacements can also provide a direct understanding and visualization of advection and diffusion mechanism in large scale of flow networks.

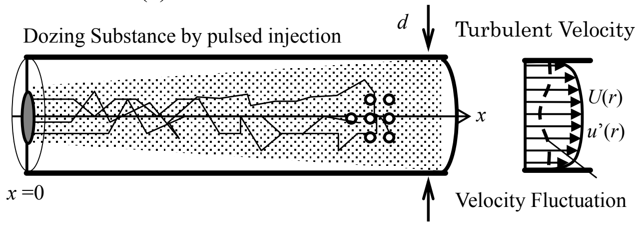
2.1 *Points movement*

In the DTPM simulation, the displacements of points are carried out by considering the average turbulent velocity profile and turbulent intensities of a circular airway as function of its radial position. Figure 2 shows schematic flow field in Cartesian coordinates (*x, y, z*) and definitions of variables to describe positions of each tracer point in circular airway with radius *R* or diameter *d*(=2*R*). In real condition, airway' cross-sectional area may vary and difficult to be considered. For the simplicity, it is ideally assumed to be circular airway with a constant cross sectional area during certain length.

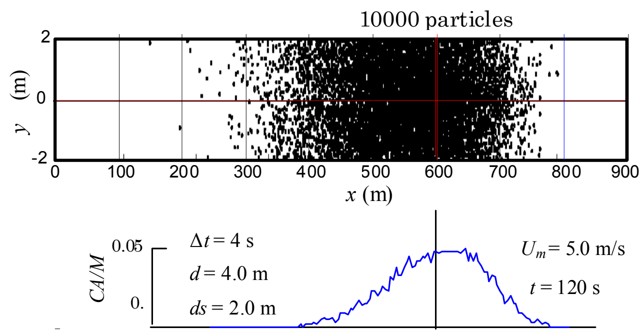
The distance from the initial dozing position of tracers in longitudinal flow direction is expressed as *x*(m), *r*(m) is radial position from airway center on perpendicular line to wall surface, and φ is tangential direction perpendicular to *x* and *r*. For fully developed turbulent flow, mean velocity in *r* and φ directions is zero. The scheme is calculated based on cylindrical coordinates as it is easier to describe the velocity vectors in this way.



(a) Coordinate and variable definition



(b) Schematic moving process of tracer points



(c) Typical example of distribution of points and concentration in flow direction, *x*

Figure 2. Schematic definitions of tracer point movements in (*x-y*) and (*y-z*) cross sections.

The velocity of each point is given based on its radius position from average turbulent velocity and fluctuation profiles, U_m (m/s) and $u'(r)$, $v'_r(r)$ and $v'_\varphi(r)$. Turbulent diffusion is characterized by its stochastic velocity fluctuations. The velocity at a given specific position fluctuates around its mean value. Its fluctuation intensity is known as root mean square (r.m.s) values, which varies as function of *r*. The time averaged flow velocities and the turbulent intensities (r.m.s values) at a certain position in cylindrical coordinate system (x, r, φ) are defined as (U, 0, 0) and (u', v'_r, v'_φ) respectively.

A stochastic approach is applied to determine the point's diffusion process in the turbulent airway flow. In present numerical model, it is supposed that the point movements are based on turbulent eddy motion, which satisfies Gaussian Probability Density Function (GPDF) with standard deviations equal to turbulent intensities or r.m.s value of velocity fluctuations in each direction (Rouse 1959). In the simulations, three pseudo-random numbers follow GPDF were generated using Box Muller algorithm to calculate turbulent velocity vector (u', v_r', v_φ'). The Reynolds stress model to represent the time-averaged correlation between longitudinal and radial velocity fluctuations is applied. For the boundary condition at wall, a reflection boundary scheme is used as proposed by (Szymczak & Ladd, 2003)

Further details on numerical schemes can be found in Widiatmojo et al. (2013 a,b).

2.2 *Numerical Scheme for flow separation at junctions*

A scheme to treat the calculation of flow separation at the junction is also considered in this numerical study. Let $n(i)$ be the total number of junction i connecting airways, and junction number is denoted as k while the definition of k^{th} junction which is connected to node i is defined as $j=J(i,k)$, for $k=1 \sim n(i)$. Figure (8) shows the numbering of each connected junction to one particular junction. For an example, there are three junctions which connected to junction #15. These node are denoted as 14=J(15, 1), 16=J(15,2) and 22=J(15, 5). The actual junction numbers connected to junction #15 can be any number for k = 1~3, (except #15). These mathematical numbering and connecting definitions can provide generalized numerical schemes and codes to treat complex ventilation networks.

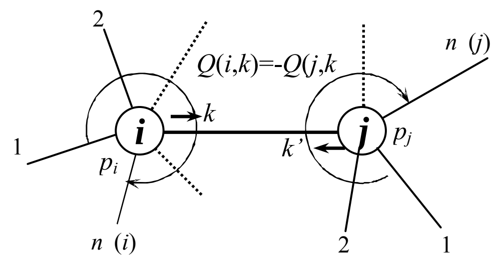


Figure 3. Definitions of airways connection and variables for network flows (Sasaki & Dindiwe, 2002)

The static pressure, p_i (Pa), at node i is defined as flow potential induced by fans and natural ventilation, not including atmospheric static pressure due to elevation difference and airflow dynamic pressure. Furthermore, let define the thermal natural ventilation pressure upon an airway from i to j as $\Delta v_{i\text{-}j}$ (Pa), calculated from level difference between two nodes, the gravitational acceleration and the average air density difference between airway and the atmosphere at the datum elevation. The total flow potential to drive airflow from node i to j, denoted by ΔH_{ik} (Pa), is given by

$$\Delta H_{ik} = p_i - p_j + \Delta v_{ik} \quad (1)$$

Airflow quantity for fully developed turbulent flow rate from i to j (see Figure 3), $Q(i,k)$ (m^3/s), is expressed by

$$Q(i,k) = \delta_{ik} \left| \frac{\Delta H_{ik}}{R_{ik}} \right|^{\frac{1}{2}}; \quad \delta_{ik} = \begin{cases} +1 : \Delta H_{ik} \geq 0 \\ -1 : \Delta H_{ik} < 0 \end{cases} \quad (2)$$

where R_{ik} (Pa/(m^3/s)n) is resistance of the airway, and δ_{ik} is the sign indicates flow direction. Thus, $Q(i,k)$ is positive when the airflow is directed from i to j. Supposing, a point is arrived at node i, based on the Kirchhoff's first law of nodal flow, the probability, $\varepsilon(i,k)$, to transfer to the next connected node j=J(i,k) is defined as:

$$\varepsilon(j,k) = \frac{\delta_{ik} \cdot Q(i,k)}{\sum_{k=1}^{n(i)} \delta_{ik} \cdot Q(i,k)} \quad (3)$$

Then, a uniform random number is generated to decide which airway a point must be transferred based on Equation (3) (Widiatmojo, 2013).

The only required parameters for present scheme are the network data, such as connectivity between nodes, length of airways, flow rate and flow velocity.

3 EXPERIMENT ON TIME DELAY OF POINTS BY RECIRCULATION FLOWS

3.1 *Experiment on air residence time in cavity*

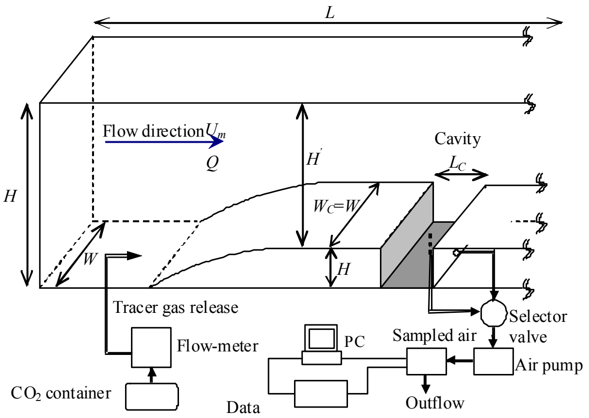
The laboratory scaled experiments have been done by constructing a single side rectangular cavity in the bottom of a square-cross section open loop wind tunnel. The flow in a cavity along an airway is characterized by recirculation flow as shown in visualization photos presented in Figure 4.

The aim of this experiment is to determine average time delay or rate of dilution of air in a semi-enclosed space by measuring decay rate at which tracer concentration is reduced with time.

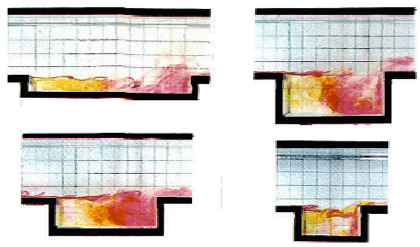
Figure 4 also shows the schematic depiction of the experimental setup measuring decay time of a gas with the cavity. In this experiment, carbon dioxide (CO_2) gas was used, and continuously released into the cavity and then stopped after constant concentration in the cavity was achieved. The decay of CO_2 was observed for the different sets of mean flow velocity and cavity's aspect ratio (width/depth).

3.2 *The delay time model by cavities for DTPM*

One of the most important considerations is how to model the delay time due to recirculation flow in cavities along airways. In real mine, the cavities are largely exist and its size and geometry are varied variously. The distribution, size and shape are highly uncertain and impractical to be quantified.



(a) Experimental setup



(b) Visualization photos of cavity recirculation-flows

Figure 4. Schematic depiction of the laboratory testing to measure decay time of gas in a cavity

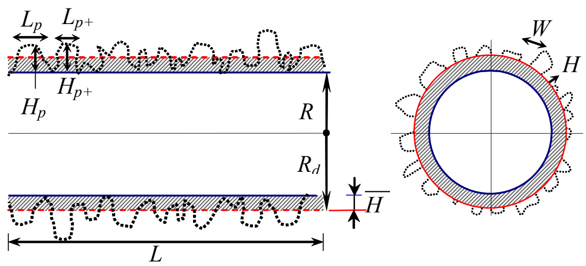


Figure 5. Simplified model of small cavities distributed around circular airways that is treated as extended region of airways

In this study, it is assumed that the cavities can be estimated by equivalent volume of concentric annulus surrounding airways as illustrated in Figure 5. This equivalent dead space volume can be adjusted by varying the dead space radius, R_d (m).

The dead space ratio; ψ(%) is represented as the ration of dead space area against original airways' cross sectional area:

$$\psi = \left[\left(\frac{R_d}{R} \right)^2 - 1 \right] \times 100\% \tag{4}$$

The advection of trapped gas/dust inside the cavities is complex and unclear depending on its geometry, shape and mean velocity in the airway. Here, it is supposed that in the absence of velocity profile, the velocity in the dead space may be given with a low constant velocity ($U \cong 0.01$ m/s) in longitudinal direction. Similar concentration-time curves of arriving points were obtained by giving U =< 0.01 m/s. This numerical treatment gives delay time on point movement parallel to the flow direction.

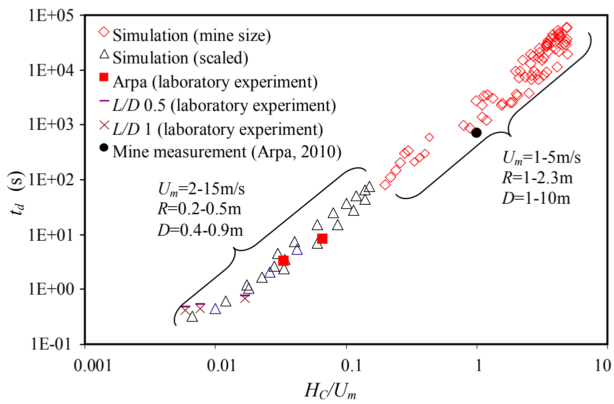


Figure 6. Relationship between average time delay, t_d, and dead space ratio

To verify the dead space model, a simple simulation was carried out. Simulations are performed for different sets of flow conditions of average airway velocity, radius and depth of cavities. These parameters are classified into two groups. One is a group that considers flow conditions with size range for laboratory model with average flow velocity U_m=2 to 15 m/s, radius R=0.2 to 0.5 m, cavity depth H_C=0.4 to 0.9 m. The other group has flow properties similar to the size of mine airways, U_m=1 to 5m/s, R=1 to 2.3 m, H_C=1 to 10 m. However, to compare with the experimental results, a parameter showing average delay time due to recirculation flow in a cavity must be firstly determined. A characteristic retaining time, t_d (s) is introduced based on the decay curve obtained from the measurements. As shown in Figure 6, the numerical simulation results, t_d vs. H_c/U_m, indicate good agreement with various measurements results using different sizes of cavity.

Further results of the comparison between normalized values of $t_d U_m / H_c$ vs. ψ(%), suggest that the present dead space assumption is reasonable to represent the delay time caused by recirculation flows in cavities.

4 DTPM SIMULATION RESULTS

4.1 *Straight-single airway*

The effects of dead space ratio, ψ(%), on the points' distribution in straight airways are presented in Figures 7 for U_m =2 m/s, d=3 m. Concentration-time curves were calculated as the points' arrival distribution at the distance, L=500m. These results were compared with 1-D advection-diffusion Equation (Widiatmojo et al. 2013b).

As can be seen in figure 7, when the higher value of dead space ratio is applied, the unsymmetrical shapes of concentration-time curves are increased. This may be identical with the trailing effect phenomena observed in tracer gas measurements in mine (Widodo et al. 2008).

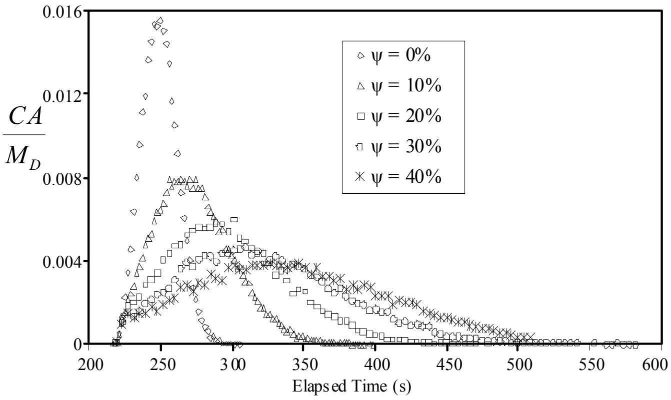


Figure 7. Simulation results using DTPM for different dead space ratio, ψ (%) for U_m =2 m/s, d=3m.

4.2 *Network Simulation*

The tracer gas measurements conducted at the ventilation network of Kushiro Coal mine Co, Ltd (see Figure 8) are simulated using DTPM. The network data used as input is the actual ventilation data when the measurements were conducted and was provided by the company. Tracer gas was released into main intakes, namely Daini and Harutori intake shafts.

The Sulfur Hexafluoride (SF_6) gas was filled into balloons to make pulse release of tracer gas by breaking it. To obtain the volume of SF_6, the weight of balloons were measured before and after filling, while also measured its diameter for the calculation of buoyancy correction. To monitor the arriving gas concentration, a gas monitor was placed at the main fan. This gas monitor is capable to detect SF_6 concentration as low as in 10 ppb resolution.

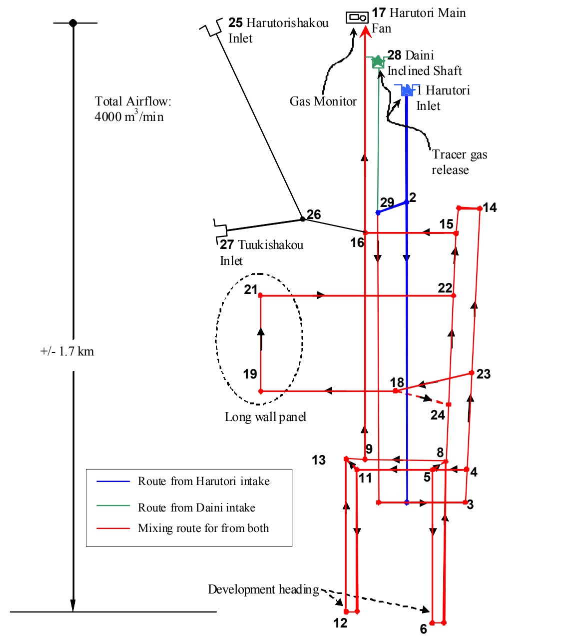
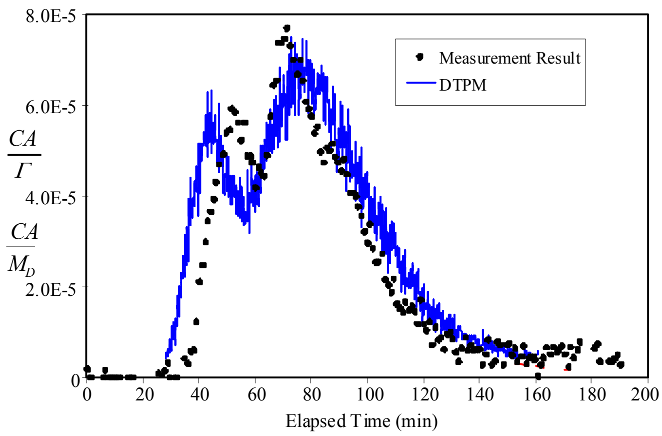
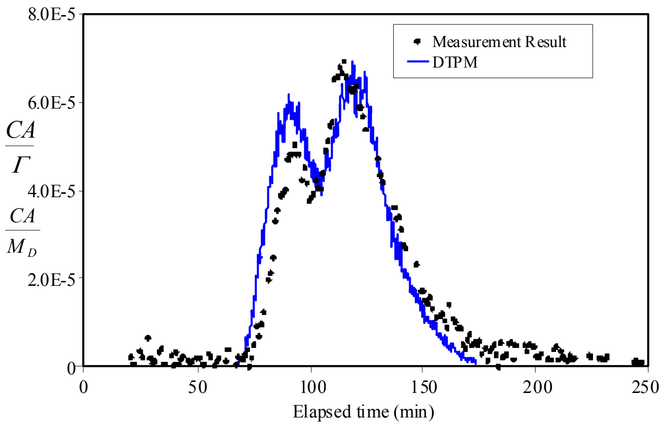


Figure 8. Kushiro Coal Mine's ventilation network (2011)



(a) Releasing SF_6 gas from Daini inlet



(b) Releasing SF_6 gas from Harutori inlet

Figure 9. Comparisons of the measurement result and simulation result on two measurements at the mine site

Each airway has different value of dead space. It can be evaluated that vertical shaft with smooth lining has very small dead space ratio close to zero, while long-wall coal cutting faces or usual airways with iron or wood supports have large volume of dead spaces. For the simplicity, the uniform values of dead space ratio were set for all airways (ψ=35%). Figure 9 shows comparisons of measurement and simulation results for tracer gas releases from Daini and Hautori inlets, respectively in Kushiro Coal Mine. The DTPM could determine airflow quantity distributions from multiple inlets to an exhaust fan.

5 MINE MEASUREMENTS AND NUMERICAL SIMULATIONS BY PRESENT SYSTEM

A large size of underground mine has generally multiple inlets and sometime multiple main exhaust fans. For mine ventilation planning and analysis, engineers may need to determine the airflow quantity connecting each intake to each exhaust. This particular analysis is impractical to be conducted through ventilation survey or common ventilation network simulator as airflow mixing at junctions is occurred.

The tracer gas method could calculate the percentage of gas volume arrived at a monitoring position (such as a main fan) by comparing with initial amount of released gas. With using same procedure, DTPM simulation has been applied successfully for a particular situation in the mine ventilation network as described above, then flow amount and airflow path have been analyzed by tracking points from the releasing position to the main fan.

6 CONCLUDING REMARKS

An integrated numerical simulation method, Discrete Tracer Points Method (DTPM), a part of the mine ventilation simulator, has been used to analyze turbulent diffusion in airways and traveling time from inlets to exhausts in the mine ventilation network. This DTPM method uses the calculation scheme by making tracer points moving based on assumptions of turbulent velocity profile, velocity fluctuations, Reynolds stress, and turbulent intensities in airflows. The DRPM numerical scheme is simple to treat network flows, and it is free of grid generations and calculations of the concentration gradient.

The present paper can be summarized as:

1) A new calculation model to give time-delay of points in dead spaces has been presented based on laboratory scaled experiments using tracer gas and the rectangular cavity model constructed in the open-loop wind tunnel.
2) The DTPM using the new decay model for dead spaces has been applied successfully for tracer gas diffusion in the ventilation network at Kushiro Coal Mine by setting dead space ratio ψ=35%.
3) The DTPM network-calculation schemes can be used to determine airflow quantity distributions from multiple inlets to exhaust fans.

The DTPM has showed a potential to reduce its calculation time than other numerical methods to simulate diffusion properties in turbulent flows at mine ventilation network airways. However, it needs further improvements in several aspects, for examples, consider other different cross sectional shape of airways and more detail on the dead spaces model including its geometry, orientation angle against main flow

ACKNOWLEDGEMENTS

The part of present research was financially supported by KAKENHI (24360372) and the fund for cooperative research between Liaoning Technical University and Kyushu University. Authors also thank to Kushiro Coal Mine Co., Ltd. for supporting the tracer gas measurements, and Dr. Masanori Matsumura, Kitami Institute of Technology for allowing authors to conduct wind tunnel test.

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