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Turbulent diffusion coefficient in mine airways

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ABSTRACT: The ventilation measurements by tracer gas method at Pongkor gold mine show that effective diffusion coefficient, *E*, at straight airways indicated a similar range of measured one by the laboratory experiments which can be estimated by Taylor equation. On the other hand, *E* of the curved airways in the mine was estimated as larger than that of the straight ones (1.5 to 32 times than that obtained by the Taylor equation and these have been compared with the data measured in Kushiro coal mine, Japan). The curved mine airways, with small curvature against airway radius and complex velocity profile, possibly give concentration – time curves with long tailings, thus those airway conditions could make larger *E*. Laboratory experiments of gas diffusion by a pulsed injection of small amount gas, into straight and curved airways, have been conducted in order to investigate a range of *E* in mine airways. The plots of *E* against Reynolds number show that the present laboratory results of straight-long airways are almost close to one calculated by Taylor equation. On the other hand, the values of *E* measured at curved single-direction airways were smaller than that of the straight airways, which may be due to effects by secondary vortexes flow in the curved airways.

1 Introduction

One of important parameters for gas diffusion in mine ventilation is a diffusion coefficient which represents the spreading of gas injected from the upstream of mine airways. For tracer gas analysis, the coefficient is use to calculate the concentration of gas at the downstream so airflow quantity and fresh air routes from inlet to the outlet can be estimated. The diffusion coefficient can be obtained from matching the solution of advection-diffusion equation with the concentration – time curves measured for pulsed gas injection method (Widodo et al., 2007).

Taylor (1953 and 1954) presented the equations to estimate effective diffusion coefficient in straight tubes with turbulent flows by laboratory experiments. For curved tubes, Van Andel et.al (1964) reported the experimental results of gas diffusion coefficient for laminar flows in a curved tube, which were smaller than that in a straight tube due to secondary flow effects. Daskopoulos and Lenhoff (1988) also observed same phenomenon by numerical simulation approach. Sasaki and Dindiwe (2002) have found that turbulent diffusion coefficient in a mine airways were larger than an estimation by Taylor equation. With the few measured data on the diffusion coefficient in turbulent flow through mine airways, further measurements and analysis were needed to evaluate the parameters influence the mine-airways turbulent diffusion coefficient.

In this study, mine ventilation measurements by pulsed injection of tracer gas at the Pongkor gold mine have been carried out through straight and curved airways picked up in the mine ventilation. The laboratory experiments on the air flow tubes have been also conducted and compared with Taylor equation. Furthermore, effects of airway curves on gas diffusion in mine ventilation airways have been discussed.

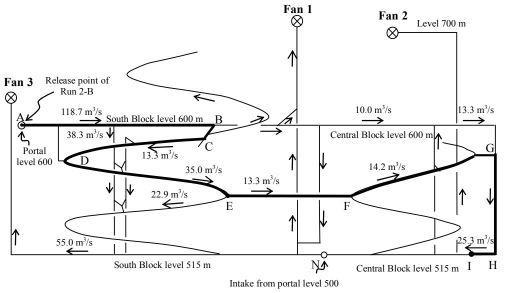
2 Measurements

2.1 Field Measurements in Mine Airways

The area carried out the tracer gas measurements was the Ciurug vein of the Pongkor mines, which is fully mechanized with cut and fill stoping located at an elevation 515–700 m above sea level. Fresh air is supplied from two intake portals that are located at a level of 515 m at the central block and at a level of 600 m at the south block. It is distributed to areas of the south, central and north blocks. There are three vertical shafts connected to three main fans to exhaust the air, namely CURB1 (fan 1; 630 Pa, 53.3 m3/s), Level 700 (1869 Pa, 49.9 m3/s), and RC IV

(664 Pa, 55.0 m3/s) (see Figure 1), respectively. Its total airflow rate is 153.3 m^3/s.

The tracer gas was released from the inlets by breaking SF_6 balloons with a volume of 0.037 – 0.080 m^3. Gas concentration in the airflows was measured at downstream positions, using a photo-acoustic gas monitor with 10 ppb resolution and 40-s measurement interval (Bruel & Kjaer Model 1302, Innova AirTech Instruments, 2006). The injection and measurement points of SF_6 are shown in Figure 1. During the measurements, the airflow quantities were monitored with an anemometer continuously.

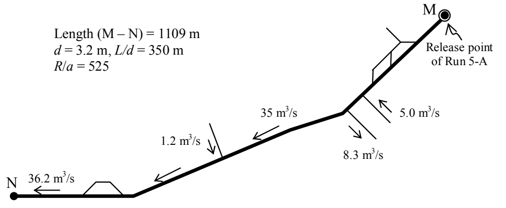


Length (A – I) = 1904 m, d = 3.97 m, L/d = 479.5
R/a = 5.7 – 99.7

Data R/a from A to I:

A-B	= 49.8, 26.0	D	= 5.7	G	= 12.
B	= 6.5	E	= 10.9	H	= 12.
C	= 11.3	E-F	= 13.0	H-I	= 33.

(a) Curved mine-airways (Run 2-B)



(b) Straight mine-airways (Run 5-A)

Figure 1. Airways conditions for measurements in the Pongkor mine

The airflow routes and quantity were predicted with flow measurements and numerical simulations using ventilation network simulator (MIVENA Version 6.2 and VENTSIM Version 3.7.1b) before the tracer gas measurements. In the case of short distance airways, the measurements were taken in a short time (less than 10 min) because of small diffusions in its flow direction. Conversely, measurements of long distance required several hours to return the concentration to its base line, due to larger and longer convective diffusion. The ratio expressing distance over equivalent diameter, d, (= 4 times hydraulic mean depth), of the measured airways, L/d, was selected from 70 to 750 in the Pongkor mine.

2.2 Experiments

Laboratory experiments have been conducted by pulsed injection of small amount gas into straight and curved tube flows. Measurements of gas diffusion were carried out at a laboratory room, Kyushu University. Methane gas was selected as a tracer gas, because the methane gas monitor satisfied requirements on gas concentration range, measurement resolution, response time and data sampling interval. Horizontal-circular airways with 3000 and 1200 of length over diameter ratio (L/d) were used in considering the mine airways. The coordinate system for curved airway is shown in Figure 2, with R is radius of curvature, a is radius of airway, and (x, y, z) are the Cartesian coordinates. The curvature ratio (R/a) in the experiments was set as 80 or 120.

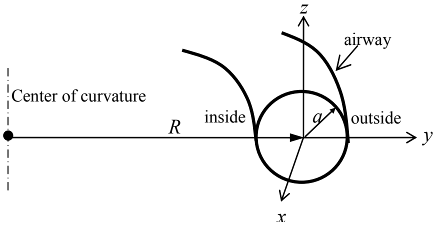


Figure 2. Coordinate system of a curved airway

The schematic Figure of laboratory experimental apparatus is shown in Figure 3. The airways are reinforced hose- tubes of 25 mm in diameter (Togawa sangyo, Tetron blade hose, 25×33, 0.6 MPa, type 10×16, 1.1 MPa), 30 m in length and placed horizontally. Air flow of Reynolds number Re = 7830 – 26600 on straight airways were generated by an exhaust fan. For curved airways, the blower fan was used.

Pure methane gas was supplied by the set of injection apparatus which consist of a gas bag and injector (Cole Palmer, Master Flex, Model 7518-10) controlled by an automatic timer switch (TOP signal, Cat. No. 2078). A pressurized small balloon was used to inject methane gas into turbulent flow, because shorter injection-time required for higher velocity flow. Pulsed injection was carried out possibly by breaking it with a needle. The constant gas volume of 2.4 cc in atmospheric condition was injected.

Gas concentration was measured by an original designed infrared adsorption gas detector using a 3.4μm He-Ne laser tube and an infrared sensor. Data acquisition interval was set as 0.1 s due to short traveling time by high velocity of the flow (maximum; 20.9 m/s and Re = 26600).

Velocity Profiles in airways were measured by a hot wire velocimeter (KANOMAX, Model 1000). Figure 4 shows the velocity profiles measured on y-coordinate for straight and curved airways. It was confirmed that air flows in present tubes have typical turbulent velocity profiles. The center of maximum velocity on curved airway shifted to outside by secondary vortexes due to centrifugal force.

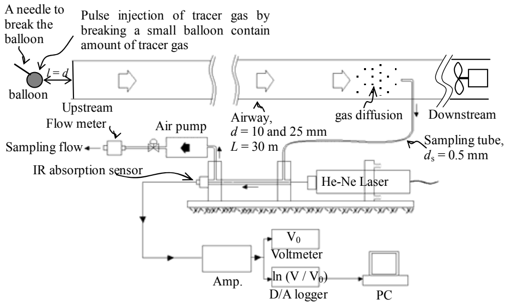


Figure 3. Schematic Figures showing tracer gas concentration measurement

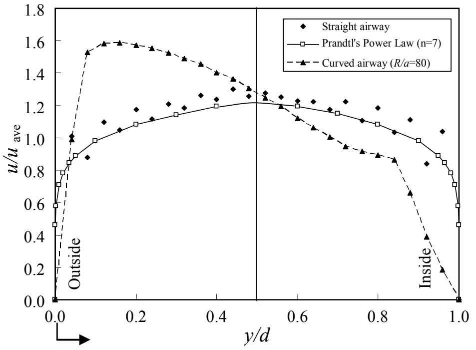


Figure 4. Velocity profiles for Re = 5100

3 Measurement and Analysis

3.1 Numerical Simulation Method and Procedure

According to Taylor (1954), the solution of equation advection-diffusion equation for one dimensional flow is given as follows:

$$c\,(x,t) = \frac{V}{2A\sqrt{\pi Dt}}\exp\left(\frac{-(x-\bar{u}t)^2}{4Dt}\right) \qquad (1)$$

where:
$c\,(x,t)$ = gas concentration in x-positions and t-time (m^3/m^3)
V = volume of gas at the origin (x=0, t=0) (m^3)
A = cross sectional area of airway (m^2)
D = virtual diffusion coefficient (m^2/s)
$\bar{u}$ = uniform flow velocity.

For turbulent flow region (Re>4000), the virtual diffusion coefficient was also presented by Taylor as,

$$D = 10.1au^{*} \quad ; u^{*} = \bar{u}\sqrt{\frac{f}{8}} \qquad (2)$$

where:
u^* = friction velocity (m/s)
$\bar{u}$ = average velocity (m/s)
f = friction factor

Equation (2) was derived from the experiments conducted on a straight tube and homogeneous turbulent conditions by Taylor. In mine ventilations, on the other hand, ideal and homogeneous conditions are difficult to set up due to a wide variation of airway friction factors, mixing at auxiliary fans and air flows joining at airway nodes. To analyze the concentration – time curves of mine measurements, a numerical history matching method has been developed (Sasaki and Dindiwe 2002). The tracer gas concentration at a downstream node is simulated using,

$$C_i(t) = \int_0^t \frac{C_{i-1}(\tau)\,Q_i}{2A\{\pi E_x(t-\tau)\}^{1/2}}\exp\left[-\frac{\{X-\bar{v}(t-\tau)^2\}}{4E_x(t-\tau)}\right]d\tau \qquad (3)$$

where:
C_i = gas concentration at a downstream node (m^3/m^3)
$C_{i\text{-}1}$ = gas concentration at an upstream node (m^3/m^3)
t = elapsed time from gas injection (s)
Q_i = air flow rate on an airway (m^3/s)
τ = time (s)
A = cross-sectional area of an airway (m^2)
E_x = effective turbulent diffusion coefficient in flow direction (m^2/s)
X = distance between two nodes (m)
$\bar{V}$ = average gas convection velocity in an airway (≈70% of average air velocity in a cross sectional area, $\bar{u}$) (m/s)

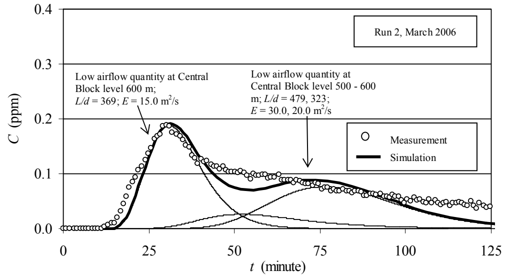
Equation (3) has been applied for numerical simulations based on linear summations of results calculated with equation (1) with discrete tracer gas volume, ΔQ_G, on the upstream node. The time, τ, used in equation (3) is divided by small interval, $\Delta\tau$ (=0.08 to 1 s), according to its integration. At an origin node releasing tracer gas, $\Delta Q_G = C_{i\text{-}1}(\tau)Q_i\Delta\tau$, which is equal to SF_6 volume (scc) of a balloon.

The match between the simulation and measurement curves in peak values and delay times give a reasonable possibility of evaluating fresh air routes, airflow quantity and effective diffusion coefficient. The numerical simulations were done for each airflow route with input data, which are airway area and length, airflow quantity, and effective diffusion coefficient. The average airflow velocity $\bar{u}$ and the effective diffusion coefficient E have been adjusted properly to match with the measurement curve.

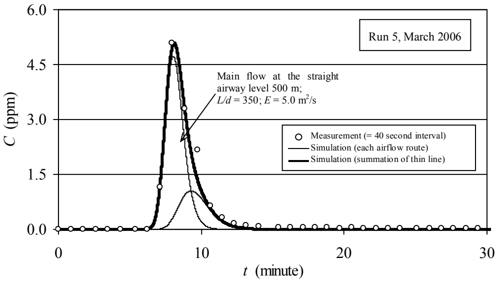
3.2 Diffusion Coefficient in Mine Airways

Two roots consisting relatively curved and straight airways connected at the Pongkor mine are shown in Figure 1 and Table 1. The airways for Run 2-B, the airways with complex curving, are connected at junctions of A to I. On the other hand, Run 5-A is simple and straight. It is shown that curvature ratio, R/a, of Run 5-A is much larger (=525) than that of Run 2-B (=5.7 to 99.7).

The diffusion coefficients were obtained from matching the analytical results of concentration – time curves with the measured ones. The time difference from a point increasing and another point returns to a baseline and the peak concentration value in the concentration – time curves gives information of the diffusion coefficient (see Figure 5).



(a) Curved airway (Run 2, R/a = 5.7 - 99.7)



(b) Straigth airway (Run 5, R/a = 525)

Figure 5. Concentration – time curves measured and analytical results for measurements at Pongkor mine airways

Figure 5 shows that the diffusion coefficient in the curved mine-airway (Run 2-B) is higher than that in straight mine-airway (Run 5-A). This may be due to small curvature ratio in curved mine-airway and complex velocity profile at the junctions which could make a large tailing effect on concentration – time curves measured.

However, some data show reverse results that the diffusion coefficient in curved airways smaller than that estimated by Taylor equation (see Figure 7).

3.3 Diffusion coefficient in experimental airways

The measured concentration-time curves and the analytical solutions by Taylor's equation (2) for straight and curved airways in present experiments are shown in Figure 6. It is shown that the concentration-time curves are almost close Gaussian distribution. Ones of curvature ratios (R/a = 120) has longer "tail" after the peak and the "tail" in straight airways are longer than that in curved airways. It may be due to the acting of secondary vortex flow generated at curved airways that enhance lateral mixing and may reduce the gas dispersions. The effective diffusion coefficient is shown in Table 2.

Table 1. Conditions of curved and straight airways in the Pongkor mine ventilation

Run	*R/a*	*n.curve*	*f*	*Re*	*L/d*	*D* (m^2/s)
Curved						
Run 1-A	4.2 – 63.8	5	0.10	1.12E+06	139.2	9.86
Run 1-B	1.6 – 49.8	11	0.13	6.65E+05	239.1	6.66
Run 1-C	1.6 – 49.8	10	0.13	7.21E+05	222.4	7.22
Run 1-D	2.1 – 49.8	9	0.13	9.77E+05	150.4	9.78
Run 2-A	3.5 – 63.8	10	0.15	6.77E+05	369.1	7.49
Run 2-B	1.0 – 99.7	14	0.15	5.52E+05	479.5	6.01
Run 2-C	1.0 – 49.8	12	0.15	4.53E+05	323.5	4.92
Run 3-A	1.6 – 51.0	8	0.09	1.32E+06	133.4	11.42
Run 3-B	1.6 – 51.0	11	0.09	1.18E+06	142.9	10.17
Run 3-C	1.6 – 51.0	10	0.09	1.24E+06	139.2	10.94
Run 3-D	1.6 – 51.0	15	0.10	9.83E+05	205.0	8.93
Run 3-E	1.6 – 51.0	15	0.10	9.53E+05	201.0	8.67
Run 3-F	1.6 – 51.0	16	0.10	9.59E+05	215.8	8.78
Run 4-A	4.2 – 63.8	5	0.10	3.95E+05	68.9	3.49
Run 4-B	1.6 – 49.8	11	0.13	3.14E+05	247.3	3.23
Run 4-C	1.6 – 49.8	10	0.13	3.24E+05	221.8	3.29
Run 7-A	-	16	0.05	1.10E+06	2915	6.11
Straight						
Run 5-A	525	-	0.13	7.13E+05	352.9	7.29
Run 5-B	525	-	0.13	6.96E+05	361.2	7.08
Run 6-A	525	-	0.11	4.77E+05	716.7	4.53
Run 6-B	525	-	0.11	4.68E+05	725.1	4.45
Run 6-C	525	-	0.11	4.73E+05	726.1	4.49
Run 6-D	525	-	0.11	4.38E+05	745.0	4.14

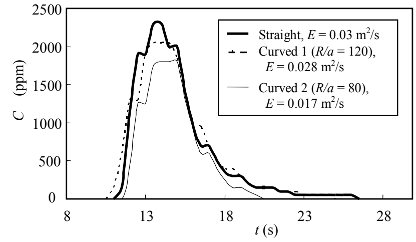


Figure 6. Gas concentration – time curves measured and analytical results for Re = 5100

Table 2. Comparison of diffusion coefficients for curved and straight airways in experiment

Run	*R/a*	*Re*	*L/d*	u_{max} (m/s)	$\bar{u}$ (m/s)	*D* (m^2/s)	*E* (m^2/s)
Curved							
Run 40	120	5.1E+03	1200	5.1	3.2	0.028	0.028
Run 50	80	5.1E+03	1200	5.1	3.2	0.028	0.017
Straight							
Run 1	-	2.66E+04	1200	20.9	17.0	0.120	0.173
Run 2	-	2.50E+04	1200	19.7	16.0	0.113	0.160

Run 3	-	2.37E+04	1200	18.6	15.2	0.108	0.137
Run 4	-	2.12E+04	1200	16.6	13.5	0.098	0.097
Run 5	-	1.97E+04	1200	15.5	12.6	0.092	0.080
Run 6	-	1.83E+04	1200	14.4	11.7	0.086	0.074
Run 7	-	1.61E+04	1200	12.6	10.3	0.077	0.065
Run 8	-	1.31E+04	1200	10.3	8.4	0.064	0.061
Run 9	-	9.83E+03	1200	7.7	6.3	0.050	0.050
Run 10	-	6.44E+03	1200	5.1	4.1	0.035	0.045
Run 30	-	5.1E+03	1200	3.9	3.2	0.028	0.030

Notes: 1. *D* : Taylor diffusion coefficient (Eq.2).
3. Airway diameter = 25 mm

4 Discussion on Turbulent Diffusion Coefficient

Taylor equation (2) indicated a relationship between velocity and diameter of airway with the effective diffusion coefficient. Therefore, in order to evaluate this relationship for mine airways, the diffusion coefficients for curved and straight airways and also with the field data are plotted against Reynolds number, Re, as shown in Figure 7.

Figure 7 shows that Taylor equation gives a relationship that the diffusion coefficient increases with Re in a power equation. On the other hand, the effective turbulent diffusion coefficients evaluated for mine ventilations do not have strong relationship against Re.

The present results for laboratory experiments in straight airways follow Taylor equations. It is shown that *E* of laminar and turbulent flows for curved airways, are smaller than that for straight airways. The diffusion coefficient is influenced linearly with curvature ratio, *R/a*.

The diffusion coefficients, *D*, predicted by Taylor equation (2) for friction factor *f* = 0.05 to 0.20, show almost same range with the present results of effective turbulent diffusion coefficient, *E*, evaluated for straight airways and some of curved airways. However, for some data of curved mine-airways, the diffusion coefficients evaluated by the measurements show much higher values than that predicted by the Taylor equation.

The effective turbulent diffusion coefficient plotted against number of curvature in mine airways is shown in Figure 8. It can be shown that this relationship is not strong enough to make an empirical equation.

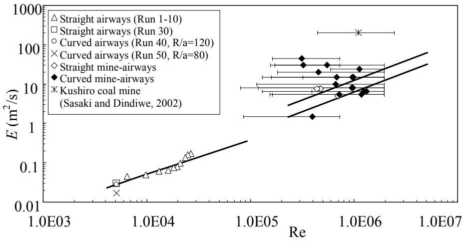


Figure 7. Relationship between effective diffusion coefficients against Re

Another relationship between the effective turbulent diffusion coefficient, *E*, against *L/d*, is shown in Figure 9. A rough relationship between *E* and *L/d* provides a suggestion that *L/d* is a parameter to estimate *E* by an empirical equation of *E* = 0.08(*L/d*). The reason of this may be considered that there are lots of mixings at nodes connecting airways, large value of airway-roughness and auxiliary fans existing along the airways in operating mines. Those make increases of *E* against *L/d* compared with the simple airways.

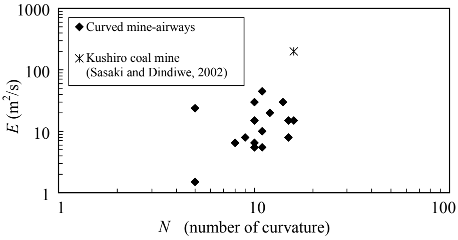


Figure 8. Effective diffusion coefficient against number of curvature in mine airways

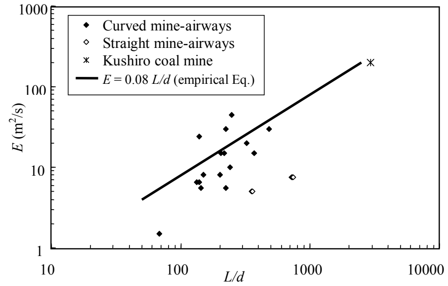


Figure 9. Relationship between effective diffusion coefficients against *L/d* for mine airways

5 Conclusion

The numerical simulations using equation (3) have been done in order to estimate the effective diffusion coefficient, *E*, by simulating the concentration-time curves measured. The *E* in the mine ventilation airways have been evaluated as *E* = 4.0 to 200.0 m^2/s.

For simple mine airways, *E* can be estimated by the Taylor equation (2) as an approximate value of the effective turbulent diffusion coefficient based on Reynolds number and friction factor of the airways. However, for complex mine ventilation airways, much higher values of *E* were evaluated based on the measurements in the mine. It can be expressed with an empirical equation *E* = 0.08(*L/d*), where *L/d* is the ratio of distance over equivalent diameter of the airway.

Effects of curvature have been evaluated by laboratory experiments. For single direction curved airways, secondary vortex flow give an effect of reducing gas dispersion in axial direction, so the diffusion coefficient becomes smaller compare with that in the straight airways.

In the mine airways, effects of curvature of airways on the diffusion coefficient could not be quantified clearly because *L/d*, roughness, and auxiliary fan occurred in the airways also influence the diffusion coefficient. However, 56% of measurements results on the curved mine-airways show a reverse result against the laboratory experiments, which *E* was larger than that of straight airways. The complex velocity profiles and larger roughness on mine airways will make stronger mixing effects on gas more than secondary vortex flow at curved airways.

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