Prediction of Climatic Conditions in Developing Roadway with Forcing Auxiliary Ventilation System*

– Control of thermal environmental conditions in locally ventilated working place (2nd Report) –

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Finite difference method is applied to simulate the thermal environmental conditions in a developing roadway with forcing auxiliary ventilation. The local heat transfer coefficients which were obtained by simulating the heat and mass transfer process in working face with CFD method are coded into the program for the prediction of the thermal environmental conditions in working face. The 3-dimensional heat conduction in surrounding strata rock, the heat and mass transfer between the airflow in the duct and roadway, the heat and mass transfer between wet rock surface and roadway air are simulated with taking into consideration the air leakage of the ventilation duct and the advance of the working face. The distribution of the air temperature and relative humidity of the air both in the duct and roadway, and their variation with time can be predicted by the program when forcing auxiliary ventilation is used. The model for the prediction of the thermal environment can provide a reliable approach to predict if a climate problem exists in the design stage, allowing suitable ameliorative measures to be tested and evaluated prior to the start of driving. It will contribute to establishing the rational method for improvement of the thermal environment, by proposing more effective technological guide in the control of heat problems in working face with auxiliary ventilation.

KEY WORDS: Auxiliary Ventilation, Developing Roadway, Thermal Environmental Condition, Working Face, Wetness Factor

1. Introduction

For controlling the climate in locally ventilated working face effectively, it is necessary to develop a proper method to predict the thermal environmental conditions in working face. Numerous studies have been made to simulate the climatic conditions in underground mines, but most of them are concentrated on a single roadway with through airflow (e.g. Yanagimoto and Uchino, 1974, 1980; Uchino and Inoue, 1982; Inoue and Uchino, 1986; McPherson, 1993; Sasaki et al., 1995). In the case of working face with auxiliary ventilation a number of researchers published the results of their studies (Shimada and Ohmura, 1990; Ross et al., 1997; Kertikou, 1997), but no satisfactorily accurate prediction method is found yet.

As a basic study on the control of the thermal environmental conditions in working face with auxiliary ventilation, CFD method was used to simulate the transfer of heat and moisture between rock surface and the airflow in a heading face with forcing auxiliary ventilation in the first report of the authors (Gao et al., 2002a). On the basis of the developed model, the distribution of local heat transfer coefficients in working face had been elucidated. The variation of heat load from strata to the ventilation air with time and wetness factor, and the distribution of rock temperature and its variation with time elapse in a working face with forcing auxiliary ventilation were discussed in that report.

The CFD method and the coded program in the previous report can be used to simulate the airflow, the heat and mass transfer process at the working face with forcing auxiliary ventilation. If CFD method is employed to simulate the heat and mass transfer process within the whole length of the roadway and surrounding rock, the number of nodes may be very large, because smaller subdivisions are required, and the equations may become unwieldy, and a simultaneous solution would be very time-consuming. This increases the computational cost substantially, too. Finite difference method can be applied to simulate the heat and mass transfer process between the roadway air and the surrounding rock fast and accurately, if the distributions of air temperature and the humidity on the cross section of the roadway do not need to be calculated. Therefore, in order to predict the thermal environment in working face effectively finite difference method is applied to simulate the heat and mass transfer process in the locally ventilated roadway.

In this paper the application of finite difference method to simulate the heat and mass transfer in a developing roadway is discussed. A program is developed to predict the thermal environmental conditions in a developing roadway with forcing auxiliary ventilation. The program can be used to make prediction of thermal environmental conditions in the working face. It can also be used to evaluate the effectiveness of the measures to be taken to solve the possible environmental prob-
lem prior to the driving.

2. Mathematical Model

The mathematical model describing the unsteady-state heat and moisture transfer between airflow and surrounding rock can been developed on the basis of the following acceptable assumptions:

1. Cross-section of the airway is taken as square. The air is discharged at a distance of 10 m from the face (Fig.1). The face advances 2 m in one cutting cycle.
2. The moisture content of air in the forcing ventilation duct is constant.
3. The rock mass surrounding airway is considered to be thermally homogeneous, isotropic, and to have a uniform distribution of virgin rock temperature.
4. Heat transfer by radiation can be neglected. Only convective heat transfer between the airway surfaces and the airflow, and between the air in the ventilation duct and in the airway are considered.
5. Partial water vapor pressure near a completely wet airway surface can be considered equal to a saturated vapor pressure. Dependence of the saturated vapor pressure on surface temperature can be approximated by a linear function. Wetness factor $f$ is employed for calculating the mass transfer from not completely wet surface, which was discussed in the previous paper.
6. Temperature dependence of the thermal diffusivity of the rock surrounding the developing airway, and of the convection heat transfer coefficient and convection mass transfer coefficient can be neglected.
7. The airflow velocity and barometric pressure in a given part of airway is constant.

Normally, if there is no other heat source, the increases in wet- and dry-bulb temperatures in horizontal airways may be attributed entirely to the flow of heat from rock to air. On the above assumptions, the problem is reduced to description of a system composed of the following parts.

For the airflow in airway:

$$Q(C_p_a + mC_p_v)\frac{\partial \theta}{\partial t} = \int \alpha(\theta_{w} - \theta) dl - 2\pi R_d k_d (\Theta_0 - \Theta_d)$$

For the airflow in duct, while $x<X_f - L_f$:

$$\frac{\partial \Theta_d}{\partial t} = 2\pi R_d k_d (\Theta_0 - \Theta_d)$$

Under the boundary conditions:

On the airway surface:

$$\partial \theta / \partial r \bigg|_{r = D / 2} = \alpha(\theta_{w} - \theta) + f \sigma L_v (m_{w} - m)$$

$$t > 0, \ q(x, y, z, t) = q(x, y, z, t) = \theta(x, y, z, t) = \theta_v$$

$$\text{Mod}(t - t_0, t_0) = 0, X_f = X_0 + L_v (t - t_0) / t_v$$

$$x = 0, \ \Theta_0 = \Theta_{00}, \ f = f_0, \ Q = Q_0$$

With initial conditions:

$$t=0, \ \theta(x, y, z, t) = \theta_i$$

$$t < t_0, \ X_f = X_0$$

where $\alpha$ = thermal diffusivity of the rock surrounding airway

$\theta_i$ = rock temperature

$\theta_v$ = virgin rock temperature

$\theta_r$ = rock surface temperature

$X_0$ = initial length of developing roadway

$X_f$ = length of developing roadway

$t_0$ = exposure time of the roadway from 0 to $X_0$

$t_v$ = time needed for one cutting cycle

$L_v$ = advancing length of working face in one cutting cycle

$\Theta_i$ = air temperature in airway

$\Theta_0$ = air temperature in ventilation duct

$a$ = convection heat transfer coefficient

$f$ = wetness factor on airway surface

$m_{w}$ = moisture content of air on airway surface

$m$ = moisture content of air in roadway

$L_v$ = latent heat of water evaporation

$Q$ = mass flow rate of air

$Q_0$ = mass flow rate of air at entrance ($x=0$)

$V$ = advancing speed of working face

$C_{pa}$ = specific heat of air at constant pressure

$C_{pv}$ = specific heat of water vapor at constant pressure

$R_v$ = radius of ventilation duct

$\Theta_{00}$ = air temperature in duct at point 2

$\phi_0$ = relative humidity at point 2

$L_f$ = distance from the outlet of ventilation duct to the working face

$k_d$ = overall heat transfer coefficient between the airflow in the ventilation duct and roadway

$$\frac{\partial \Theta}{\partial r} \bigg|_{r = D / 2} = \alpha(\theta_{w} - \theta)$$

$D$ = length of one side of the square roadway

$dl$ = differential length along the perimeter of roadway

$\sigma$ = convection mass transfer coefficient. It can be calculated from local heat transfer coefficient by use of Lewis’ formula.

The heat exchange of the airflow in the ventilation duct and that in developing roadway are considered in equations (1-2) and (1-3), respectively. In the
part of the airway where the duct is set, the temperature of roadway air is determined by the heat transfer rate from strata and that from the airflow in duct, which are written as the first and second items on the right-hand side of equation (1-2), respectively.

3. Calculation Method

Finite difference method is an effective means to obtain the numerical solutions of differential equations, which has been successfully used to simulate the thermal environmental problems by many researchers. In this study finite difference method is applied to obtain the numerical solution of the above equations. The grids are formed in the following way.

In $x$ direction (axis of airway) in Fig. 1, from the entrance of the development roadway to the duct outlet, the meshes are formed basically with intervals of 10 m. In working face (part 2 in Fig. 1), the narrow intervals of 2 m are formed. In the rock ahead of the driving face the mesh intervals are set as 0.5 m.

In $y$ direction (Fig. 2) the intervals are set as follows: from the center of the roadway to the wall surface ($j = 1, 2, \ldots, n_j 1$), uniform intervals are used. In the surrounding rock the interval expands with geometric ratio as the depth increases. The intervals in $z$ direction are taken in the same manner as those in $y$ direction.

For calculation of the temperature in the rock surrounding the roadway, the mathematical model and algorithm are the same as those used for an airway with through airflow. When airflow is ventilated locally, however, the method for calculating the thermal parameters of air is different from that with through airflow. When the roadway is ventilated locally, how ever, the method for calculating the thermal parameters of air is different from that with through airflow. When airflow is ventilated locally, how ever, the method for calculating the thermal parameters of air is different from that with through airflow.

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3.1 Heat exchange between the airflow in duct and in airway

The overall heat transfer coefficient $k_d$ between the air in the roadway and that in duct can be evaluated from the following equation.

\[
1 \over k_d = \frac{1}{\alpha_1} + \frac{1}{\lambda_d} + \frac{1}{\alpha_2} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS
rough surface of an airway with through airflow have been studied by many researchers (Yoshizawa et al., 1971, 1975; Danko and Cifka, 1984), which can be used to decide the value of \( \alpha_r \). Consequently, the distribution of local heat transfer coefficient \( \alpha_r \) on rough surface of working face with auxiliary ventilation can be calculated from equation (6). Formula (6) will be verified in another paper (Gao et al., 2002b).

3.4 Algorithms for calculating air temperature and humidity where duct is set

If at time \( t \) the temperature and the moisture content of the air in ventilation duct and those in airway as well as the temperature distribution in surrounding rock are known, then the heat and mass exchange between airflow and rock surface, as well as the heat and mass exchange between the airflow in airway and in ventilation duct can be calculated. The thermal parameters of air at time \( t + \Delta t \) can be determined consequently.

In a small element with a length of \( \Delta x \) (Fig.3), the released sensible heat from the roof of that part of the airway can be calculated according to the following equation.

\[
q_{sl} = -2 \sum_{j=1}^{n} \Delta x_j \Delta y_j \alpha_r \left[ \theta_{yj} - \frac{\theta_{ij} + \theta_{i+1,j}}{2} \right] \quad \ldots (7)
\]

where \( \alpha_r \) is the heat transfer coefficient on airway surface. It is a function of airflow rate through the element in a given roadway. The part of airflow where the ventilation duct is set can be calculated by the same method. Then the airflow on cross-section \( i \) in airway within the elemental length \( \Delta x \) can be obtained.

Heat exchange between airflow in the duct and in the airway can be expressed as:

\[
q_{di} = 2 \pi R_i \Delta x_i k_d \left[ \theta_{iy} - \frac{\theta_{ij} + \theta_{i+1,j}}{2} \right] \quad \ldots (8)
\]

The mass flow rate of air leakage from the duct into the airway within the elemental length \( \Delta x \) can be obtained by equation (5), then the sensible heat contained in the leaked air is:

\[
\Delta q_{li} = \Delta Q_l \left( C_{pa} + m_{li} C_{pm} \right) \left[ \theta_{yi} + \frac{\theta_{ij} + \theta_{i+1,j}}{2} \right] \quad \ldots (9)
\]

where \( \theta_{yi} \) is the average air temperature on cross section \( i \) in airway at time \( t + \Delta t \) and \( \theta_{ij} \) is the average air temperature on cross section \( i \) in ventilation duct at time \( t + \Delta t \).

The energy balance gives the average air temperature on cross section \( i \) in airway at time \( t + \Delta t \).

\[
\theta_{ij} = \theta_{i+1,j} \left[ C_{pa} + m_{li} C_{pm} \right] + q_{di} + \Delta q_{li} - q_{sl} \quad \ldots (14)
\]

The average air temperature on cross section \( i + 1 \) in the ventilation duct at time \( t + \Delta t \) is

\[
\theta_{i+1,j} = \frac{\theta_{i,j} + \theta_{i+1,j}}{2} \quad \ldots (15)
\]

Relative humidity \( \phi \) of air can be evaluated from the air temperature and the moisture content according to water vapor table.

3.5 Algorithms for calculating air temperature and humidity in working face

For calculating the sensible heat given out from the roof of the airway within the elemental length \( \Delta x \), into airflow in working face, equation (7) should be revised into:

\[
q_{sl} = -2 \sum_{j=1}^{n} \Delta x_j \Delta y_j \alpha_{sl} \left( \theta_{yj} - \theta_{ij} \right) \quad \ldots (16)
\]

where \( \alpha_{sl} \) is the local heat transfer coefficient on airway surface in working face.

The average air temperature in working face, can be evaluated as:

\[
\theta_f = \frac{\theta_{in} + \theta_{out}}{2} \quad \ldots (17)
\]

where \( \theta_{in} \) is the air temperature in duct outlet (point 3, Fig.1) and \( \theta_{out} \) is the average air temperature on the vertical cross section of airway where the duct outlet is set (point 5, Fig.1).

For calculating the water vapor evaporated from the roof of the airway within the elemental length \( \Delta x \) in working face, equation (8) is revised as

\[
\Delta m_{di} = 2 \sum_{j=1}^{n} \Delta x_j \Delta y_j \sigma_{di} \left[ m_{li} - m_f \right] + \Delta m_{li} \quad \ldots (18)
\]

where \( m_f \) is the humidity in working surface which is defined as the average of the humidity of the air discharged from the outlet of the duct and the humidity on the vertical cross section of airway where the duct outlet is set.

\[
\sigma_{di} = \text{local mass transfer coefficient. It can be calculated from local heat transfer coefficient } \alpha_{di} \text{ by use of Lewis' formula.}
\]

Using the same method, the sensible heat and water vapor quantity added into the airflow from the floor, two side-walls, and the head-end of the working face can be calculated. Adding up the heat and the heat consumed for evaporation of water from roof, floor, two side-walls and the head-end of the work-
ing face, the total sensible heat, latent heat and the quantity of
water vapor transferred into the airflow from the surface of the
roadway in part 2 can be calculated. Then the air temperature
humidity of airflow at point 5(Fig.1) can be determined.

3・6 Calculation procedures
The equations described above are expressed in explicit
formulations. It is possible to write the nodal temperatures and
humidity explicitly in terms of the previous nodal values. In
this formulation, the calculation proceeds directly from one
time increment to the next until the temperature and humidity
distribution is calculated at the desired state.

Algorithms and computer program for predicting the ther-
mal climate in a developing roadway with forcing auxiliary
ventilation is coded by the procedures as shown in Fig.4.

4. Verification of the Algorithm
In order to verify the developed algorithm and the coded
program, in-situ measurements were made on the thermal envi-
ronmental conditions at a developing roadway of Hishikari gold
mine, Japan, on Nov. 30, 2000.

4・1 Conditions of measured roadway
The measurement was carried out in the 70 ML North
Developing Roadway. The part of the airway where the mea-
surements were made is illustrated in Fig.5. On Mar. 7, the head-
end had been driven to the position 1-4, then the roadway was
driven continuously until May 6. The head-end advanced about
40 meters in 60 days. Then the cutting was stopped for near 7
months. On Nov. 29, development was resumed. At 12:00am,
Nov. 29, the blasting was made, and the working face advanced
2 meters. The measurement was made about 24 hours after the
blasting. The airflow rate, as well as the dry- and bulb-temper-
atures on the cross-section 1 and 2 in the duct as well as on the
cross-section 3 and 4 in the airway were measured. On one
cross-section in roadway 9 points were selected for the mea-
surement of air velocity, and 25 points were arranged for the
measurement of the dry- and wet-bulb temperatures of the air.
From the measured data, the overall heat transfer coefficient of
the ventilation duct and the wetness factor of the part of the
airway from 3 to 4 were calculated.

4・2 Conditions for simulation
The above heat and mass transfer process in the 70 ML
North Developing Roadway is simulated under the following
conditions:

Driving speed : 2 m / 3 days
Initial rock temperature: 71.3 ℃
Thermal conductivity of surrounding rock: 1.75 kcal / m² ℃
Wetness factor: 0.007
Airflow rate: 337.5 kg / min
Diameter of the duct: 0.8 m
Overall heat transfer coefficient of the duct: 9.12 kcal / m² ℃
Air temperature at point 1 (in duct): 23.85 ℃
Moisture content in the duct: 9.74 g / kg dry air

The values of the above parameters are based on the
results of in-situ measurements. The thermal conductivity of
rock is the averaged value of dry rock samples and water satu-
rated samples. The initial rock temperature is the averaged
value of the rock temperature measured at the end of the blast-
ing boreholes.

The rock around the roadway had been cooled before Mar.
7. This is considered by taking a part of airway of 20 m in length,
and assuming that this part of the airway had been ventilated for
30 days (i.e. \( t_0 = 30 \) days) before Mar. 7, 2000. This assumption
has little influence on the predicted thermal environment in
working face after it has been driven for a period of time.

During the period of suspension of operation the ventila-
tion is usually stopped. Therefore, it is assumed the airflow rate
is 1% of the normal quantity while the operation is stopped,
and the ventilation is resumed two days before the blasting at
12:00am, Nov. 29, 2000.

4・3 Results of simulation
Under the above conditions the temperature and humidity
distributions at 12:00am, Nov. 30, 2000 are calculated by the
developed program, which are shown in Fig.6.

From the figure it can be seen that the predicted tempera-
tures of air delivered at the outlet of the ventilation duct (point
2) and in the roadway (point 3) are very close to the measured

Fig.4 Basic flow chart for simulation program.

Fig.5 Layout of the measured roadway (70 ML North Developing Roadway).
A method for prediction of the thermal environmental conditions in a developing roadway with forcing auxiliary ventilation is developed using finite difference method combined with the local heat transfer coefficients which were obtained by simulating the heat and mass transfer process in working face by CFD method. The 3-dimensional heat transfer in strata rock, the heat and mass transfer between the air in the ventilation duct and that in the roadway, the heat and mass transfer between wet rock surface and airflow in the roadway are simulated with taking into consideration the air leakage of the ventilation duct and the advancement of the working face.

The distribution of the air temperature and the relative humidity of air both in the duct and in the roadway and their variation with the advance of working face can be predicted with the developed program. It is also possible to analyze the changes in the climatic conditions in working face caused by various factors such as: wetness factor of roadway surface, the heading speed, air leakage rate of the ventilation duct, overall heat transfer coefficient of the duct, etc. The program provides a reliable approach to predict whether climate problems exist in the design stage of ventilation. Therefore, suitable ameliorative measures can be tested and evaluated prior to the start of driving, in order to avoid spending large capital sums and incurring high operational cost. It will contribute to establishing the rational method for improving the thermal climatic conditions, by proposing more effective technological guide in the control of heat problems in working face with auxiliary ventilation.

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References


Fig. 6 Comparison between simulated results and measured data.