Chapter 62

ANALYTICAL SYSTEM FOR VENTILATION SIMULATORS WITH SKYLINE NODAL PRESSURE METHOD AND PRACTICAL ESTIMATE SYSTEM FOR UNDERGROUND MINE AIR-CONDITIONING

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A ventilation analytical system adapting nodal pressure method using skyline modified Choleski's decom-position scheme for network-flow analysis and a new practical system to estimate various thermal air conditions has been developed. The quasi-linear equations for solving steady-state network airflow have been described using the connective function in general forms. The skyline modified decomposition scheme has an advantage on rapid convergence and the sake of computer memory space compared with other schemes. The key part of the analysis for climatic conditions through network airways is how to estimate the temperature of the airway rock-surface with partly or full wet condition. A practical and simple solution without any iterative calculations for its estimation has been proposed. This new solution is applicable to practical ranges of airflow temperature, humidity, rock thermal properties and wetness. The present analytical system have been successfully applied to a ventilation simulator named "*MIVENA*" developed by authors.

INTRODUCTION

The many analytical systems for underground mine ventilation networks have been released to predict flow-quantity and climatic conditions of airflow using a down-sized computer (Wallace et al., 1989). Wang et al.(1985) give an excellent review of the ventilation network theory. The important requirements for ventilation network simulators are rapid calculation, stable convergent process, small memory space and user-friendly system.

The nodal pressure method is based on an quasi-linear calculation system incorporating nodal pressures as primary variables consisting simultaneous equations. The nodal pressures have to be improved by iterative calculations until satisfying the Kirchhoff's 1 or current law. The nodal pressure method is a superior process due to its simple approach for computer implementation compared with the mesh flow method needs complex procedures for the selection of meshes (Bhamidipati et al., 1985). However, it should use a direct matrix operation such as the skyline modified Choleski's decomposition scheme(MCDS) which solve the equation through a rapid and stable convergent process(Sasaki et al., 1990, 1993).

On the other hand, it is difficult to predict a detailed climatic conditions in actual underground airways with wet conditions, because it has a strong effect on airflow temperature and humidity through the rock surface temperature. The essential theory of time-variant heat flow and water evaporation from surrounding strata into ventilation air in an airway has been reviewed by McPherson(1986). A numerical model for the wet conditions is required to develop a ventilation network simulator. Danko et al.(1988) have suggested that the prediction results of mine climate by some computer codes are quite different for a case of partly wet condition. The problem to predict a mine climate is analytical modeling and practical solution for wet surface temperature reflecting actual wet conditions in airways. There are two possible models previously proposed for considering wet conditions that are sometimes confused each other. The first is wetness that expresses a ratio of mass transfer coefficient compared with that of complete wet-surface proposed by Starfield(1966). The second one is the area ratio of wet surface upon airways. In present system, the both models can be selected easily by using the practical solution for the rock surface temperature proposed.

NUMERICAL MODEL FOR NETWORK AIRFLOWS

Fundamental Flow Equations

The underground ventilation network dealt with in present system is consisted of a) airways, b) nodes connecting airways, c) junctions connecting some airways to the atmosphere(intake portals and fan inlets of surface fans). The junctions defined by c) are called 'boundary nodes' in present system.

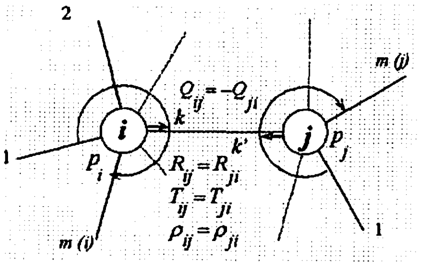

Figure 1. Definition of Network and Symbols.

Consider a network consisting of a total number of nodes N and let a nodal number be $i\,(=1\sim N)$. Figure 1 shows a schematic configuration of a network. The total number of airways connected to node i is represented by $m(i)$. The subscript $k\,(=1\sim m(i))$ is used to identify a connected airway or node. The nodal numbers connected to node i are defined using with a function denoted by $J(i,k)$. For example, when the nodal number of the kth node connected to node i is j (see Fig. 1), it is defined as,

$$j = J(i,k) \tag{1}$$

Thus all connective relations between nodes are represented by $J(i,k)$. Its usage is effective to not only save computer memory but design RDBMS for input of the network data.

The nodal pressure at node i, p_i(Pa), is defined as the static pressure induced by fans and natural ventilation not including atmospheric static pressure due to elevation difference and airflow dynamic pressure. Furthermore, let the thermal natural ventilation pressure upon an airway from i to j be Δv_{ij}(Pa) , the height from the datum level be h (m), the gravitational acceleration be

g(m/s^2), and the air densities at each airway and in the atmosphere at the datum elevation (h= 0 m) be ρ and ρ_o (=1.293 kg/m^3) respectively, the average airflow density upon the airway[$i \rightarrow J(i,k)$] be ρ_{ik} (kg/m^3), density of the atmosphere at h_{ik} [=(h_i+h_j)/2] be ρ_{oik} (kg/m^3) and differences in level and density be Δh_{ik} (=h_i- h_j) and $\Delta\rho_{ik}$ respectively. Then $\Delta v_{i\text{-}j}$ is defined as an integral value along the airway and approximated with Δh_{ik} and $\Delta\rho_{ik}$ as

$$\begin{aligned}\Delta v_{i\text{-}j} &= \Delta v_{ik} = -g\int_{h_i}^{h_j}[\rho(h,\Theta)-\rho_0(h,\Theta_0)]dh \\ &= g[\rho_{ik}-\rho_{0ik}](h_i-h_j) = g\Delta\rho_{ik}\Delta h_{ik}\end{aligned} \tag{2}$$

In present system, $\Delta\rho_{ik}$ is given as

$$\Delta\rho_{ik} = \rho_0\cdot\exp(-h_{ik}/8620)\frac{\Theta_{ik}-\Theta_0}{273+(\Theta_{ik}+\Theta_0)/2} \tag{3}$$

where Θ (°C) is the airflow temperature and Θ_0(°C) is the atmospheric temperature.

The total pressure difference to drive airflow from i to j, denoted by $\Delta H_{i\text{-}j}$ or ΔH_{ik} (Pa), is given by

$$\Delta H_{i\text{-}j} = \Delta H_{ik} = p_i - p_j + \Delta v_{ik} \tag{4}$$

Then, airflow quantity, Q_{ik}(m^3/s), is expressed by

$$Q_{ik} = \delta_{ik}\left|\Delta H_{ik}/R_{ik}\right|^{\frac{1}{n}} \quad ;\delta_{ik} = \begin{cases}+1 : \Delta H_{ik} \geq 0 \\ -1 : \Delta H_{ik} < 0\end{cases} \tag{5}$$

where R_{ik}(Pa/(m^3/s)^n) is resistance of the airway, and δ_{ik} is the sign indicating flow direction. Thus, Q_{ik} is positive when the airflow is directed from i to j=$J(i,k)$. The index n in Eq.(5) is usually equal to 2 for fully developed turbulent flow (n=2 was used in this system).

Quasi-Linear Equations

The quasi-linearized flow admittance, T_{ik}(m^3/s•Pa), between ΔH_{ik} and Q_{ik} is defined as,

$$T_{ik} = \left[R_{ik}^{1/n}\left|\Delta H_{ik}\right|^{(n-1)/n}\right]^{-1} \tag{6}$$

then Eq.(5) can be rewritten as,

$$Q_{ik} = T_{ik}\Delta H_{ik} = T_{ik}(p_i - p_{J(i,k)} + g\Delta\rho_{ik}\Delta h_{ik}) \tag{7}$$

This equation provides the quasi-linear relationship between Q_{ik} and ΔH_{ik}. When ΔH_{ik} in Eq.(6) is less than 10^{-10}(Pa), ΔH_{ik} is set as 10^{-10}(Pa) in the system.

The sum of the flows flowed into node i, q_i= ΣQ_{ik}(m^3/s), is given by

$$q_i = \left(\sum_{k=1}^{m(i)}T_{ik}\right)p_i - \sum_{k=1}^{m(i)}\left(T_{ik}\,p_{J(i,k)}\right) + \sum_{k=1}^{m(i)}g\Delta\rho_{ik}\Delta h_{ik} \tag{8}$$

In general, q_i is equal to 0 on each node according to the Kirchhoff's 1st law, except the case of existing of air quantity supplied from other sources such as a compressed air line independent of airflow from intakes. The improved nodal pressures of the (M+1)th iteration, $\{p_i\}^{M+1}$, are obtained from the M th nodal pressures $\{p_i\}^M$, and the Mth correction factors $\{\Delta p_i\}^M$:

$$\{p_i\}^{M+1} = \{p_i\}^M + \{\Delta p_i\}^M \tag{9}$$

By substituting Eq.(9) into p_i in Eq.(8), the following simultaneous linear equations relating to $\{\Delta p_i\}^M$ as unknown values is obtained.

$$\left[A_{ij}\right]^M\{\Delta p_i\}^M = \{b_i\}^M \tag{10}$$

where $[A_{ij}]^M$ is the admittance matrix of order NxN and $\{b_i\}$ is the vector of order N at the M th iterative calculation. These are expressed as,

$$\left.\begin{array}{lll} A_{ii} = \sum_{k=1}^{m(i)} T_{ik} & & (i=1\sim N) \\ A_{ij} = -T_{ik} & & (j=J(i,k)) \\ A_{ij} = 0 & & (j\neq J(i,k)) \\ b_i = q_i - \sum_{k=1}^{m(i)} Q_{ik} & & (i=1\sim N) \end{array}\right\} \tag{11}$$

The $[A_{ij}]^M$ is the symmetric matrix. The vector $\{b_i\}^M$ defined by Eq.(11) is composed of the errors associated with the continuity of flow quantity at each node i after the M th iterative calculation. Equation(10) takes the structure that $\{p_i\}^{M+1}$ converges, i.e. $\{\Delta p_i\}^M$ = {0}, as the errors of flow quantities at whole nodes decrease.

Assume that the total number of the boundary nodes is ΔN and that the nodal number at one of the boundary nodes is expressed as τ. Since ΔN pieces of inflow and exhaust air-quantities at the boundary nodes, $q\tau$(m^3/s), are unknown, the ranking of Eq.(10) becomes N-ΔN. The pressures at intake-portal nodes are given as 0, and the pressures at fan-inlet nodes are determined based on the fan characteristic curves. Thus, $\{P_i\}^M$ are given at those boundary nodes, i.e. $\{\Delta p_i\}^M$= {0}.

$$\left.\begin{array}{l} A_{\tau\tau} = 1 \quad , b_\tau = 0 \\ A_{\tau j} = 0 \qquad (j=1\sim N, j\neq\tau) \end{array}\right\} \tag{12}$$

The ranking of Eq.(10) increases by Eq.(12), however, $[A_{ij}]$ becomes asymmetric matrix. In order to convert it to a symmetric matrix, conversions of $[A_{ij}]$, given by

$$A_{i\tau} = 0 \qquad (i\neq\tau) \tag{13}$$

are used. If the all pressures of the boundary nodes are settled, the ranking of Eq.(10) becomes N.

Decomposition Scheme

In solving large-scale simultaneous linear equations, attention should be paid to calculation speed and memory space, because the matrix operation needs a comparably large memory space. In general, a half band width is used in FEM to pick up the elements that are nonzero in the neighborhood of diagonal elements. However, in the case of ventilation networks, an extreme case in which the band width equal to almost N should be taken into consideration.

The decomposition of $[A_{ij}]$, is restricted to the regime containing nonzero elements. The minimum column number of each row, $j_{min}^{(i)}$, and the maximum row number of each column, $i_{max}^{(j)}$, are defined to express the boundary of the nonzero regime as

$$A_{ij}\ ;\ i = j\sim i_{\max}(j), j = j_{\min}(i)\sim i \tag{14}$$

The four decomposition schemes; a) original MCDS, b) band matrix MCDS, c) Skyline MCDS (SMCDS) and d) ICCG have been investigated. For the case of Fukasawa Mine (Akita, Japan, N=141), the occupied area ratio of the nonzero regime is approximately 17% in the whole $[A_{ij}]$. Thus, calculation speed is particularly enhanced by restricting calculations in the regime of the under triangular matrix given by Eq.(14) with SMCDS. It is also effective for save the working memory space by using one dimensional memories to store the regime. When the SMCDS is adapted, the calculation speed is accelerated at least 6 times as compared to that of the original MCDS for the case of the Fukasawa Mine.

Fan Characteristics

A main fan characteristics between air quantity Q_f (m^3/s) and the fan-inlet static pressure P_f (>0, Pa) at a driving speed, n_d (rpm), is approximated with a Gth degree polynomial obtained by the least squares method as,

$$P_f(Q_f, n_d) = \beta^2 \sum_{\gamma=0}^{\Gamma} C_\gamma \cdot (Q_f / \beta)^\gamma \tag{15}$$

where C_g (Pa◊s/m^3) is the gth order coefficient and $\beta = n_d/n_0$ (n_0; standard rotational speed(rpm)). Γ=3 is used in the present system.

Initial Values of Nodal Pressures

The initial values for nodal pressures, $\{p_i\}^0$, are given as a constant pressure against $P_f(0, n_d)$,

$$p_i^{\,0} = -K_0 \cdot P_f(0, n_d) \qquad (i \neq \tau) \tag{16}$$

where K_0 is initial factor(=0.1~0.9). On the other hand, initial values upon boundary nodes, p_τ^0, are given by,

$$\left.\begin{array}{lll} p_\tau^{\,0} = -P_f(0, n_d) & \text{at} & \text{fan-inlet nodes} \\ p_\tau^{\,0} = 0 & \text{at} & \text{intake-portal nodes} \end{array}\right\} \tag{17}$$

Improvements of Fan Pressures

The flow quantity Q_f and the static pressure P_f at the fan inlet are improved in accordance with the following method.

With the flow quantity, Q_f^M, calculated from the Mth iterative nodal pressures,$\{p_i\}^M$, and fan inlet pressure, P_f^M, the equivalent resistance of flow R_f^M between Q_f^M and P_f^M is defined as $R_f^M = P_f^M/(Q_f^M)^2$.

When the improved Q_f is expressed as Q_f^*, the $P_f(Q_f^*, n_d)$ is equal to total pressure loss through the network, $R_f^M◊(Q_f^*)^2$. Thus Q_f^* is obtained from the algebraic equation expressed as Eq.(15) concerning Q_f^* using Newton-Raphson's method. Finally, the (M+1)th improved P_f^{M+1} can be obtained based on the improved Q_f^*. The convergence of P_f synchronizes with the convergence of $\{p_i\}$. The nodal pressure at the fan-inlet node of the (M+1)th iteration, p_f^{M+1}, is given as,

$$p_\tau^{M+1} = -P_f^{M+1} \tag{18}$$

Booster fans installed in series to provide the required air quantity are treated by the conventional method proposed by authors (Sasaki et al., 1993).

Convergence Criterion and Acceleration Factor

The number of iterations until convergence depends on the convergence criterion used. The error quantity in continuity upon individual nodes, DQ_i(m^3/s), is given as

$$\Delta Q_i = q_i - \sum_{k=1}^{m(i)} Q_{ik} \tag{19}$$

The maximum absolute value of ΔQ_i denoted by $|\Delta Q_i|_{max}$ could be regarded as a reasonable convergence criterion (a constant value of $|\Delta Q_i|_{max}$ is used in this system).

In order to accelerate the convergence, an acceleration factor w is effective (Sasaki et al., 1990). The Mth solution $\{p_i\}^M$ is given using ω as follows,

$$\{p_i\}^M = \{p_i\}^{M-1} + \omega\,\{\Delta p_i\}^{M-1} \tag{20}$$

However if ω is too large, the convergent process becomes relatively unstable. The optimum value of ω was decided by preliminary calculations. The fastest convergence has been obtained with most of the networks for ω=1.4.

For a case that airflow temperatures are fixed, the number of iterative calculations of airflow was less than 13 using constant fan pressure, ω=1.4 and $|\Delta Q_i|_{max} \leq 0.1$ m^3/min. In case of the SMCDS, the relationship between the calculation time an iteration Δt_{CPU} and the total number of nodes N is $\Delta t_{CPU} \propto N^{3/2}$ for the five networks dealt with in this study.

NUMERICAL MODEL FOR AIRFLOW CLIMATE

Prediction of air-flow temperature and humidity in underground airways is sometime difficult. Especially, the effect of full or partly wet surface is complicated and the numerical method is not so simple. The general differential equation for unsteady heat conduction in strata around an underground airway has been considered in cylindrical polar-coordinates(z, r), where the z-axis represents the centerline of the airway, r(m) is the radial distance from the z-axis. The longitudinal heat flow is neglected in present system, however its effects has been reported by Sasaki et al(1994).

Airflow Temperature and Humidity

The airflow thermal climate is affected strongly by wet degree of the airway surface. Heat flows transferred into ventilation air from the surface are sensible heat, q_S (W/m^2), and latent heat by vapor transfer from the wet surface, q_L (W/m^2). The sensible heat flux into ventilation air are transferred heat from rock surface, $q_S = \alpha\,(\theta_w - \Theta)$, and auto-compression heat, $h_C = r_a g Q \cdot \sin(-\zeta)$ (W/m), where Θ (°C) is bulk temperature of airflow, θ_w (°C) is the surface temperature, α (W/m^2 °C) is heat transfer coefficient, Q(m^3/s) is airflow quantity, r_a(kg/m^3) is air density and ζ (rad) is the angle from the horizontal surface. Thus, the rise of airflow temperature Θ along z-axis is followed by

$$\frac{\partial \Theta}{\partial z} = \frac{U \cdot q_S + h_C}{\rho_a C p_a Q} = \frac{U \cdot \alpha(\theta_w - \Theta)}{\rho_a C p_a Q} + \frac{g \cdot \sin(-\zeta)}{C p_a} \tag{21}$$

where U(m) is the perimeter of the airway and Cpa(=1004 J/kg°C) is specific heat of airflow.

Suppose χ(kg/kgDA) (DA:dry air) is absolute humidity and χ_s (kg/kgDA) is saturated one, m and m_s are vapor concentration in airflow expressed as $m = \chi/(1+\chi)$ and $m_s[= \chi_s/(1+\chi_s)]$ respectively. When the vapor concentration on wet surface, m_w, is higher than that of airflow, m, the evaporation continues from the surface. Water vapor transfer rate w (kg/sm^2) is given by $w = \phi \rho_a \beta (m_w - m)$ where ϕ (decimal number) is wetness, β [kg/(m^{2}skg/m^3)] is mass transfer coefficient which is equal to $a/\rho_a C_{pa}$ due to Lewis's law. The m_w is usually given as saturated vapor pressure for the wet surface temperature, $m_s(\theta_w)$]. The wetness f used in this system is defined as a ratio of mass transfer coefficient to that of a complete wet surface (=β). Thus, it is defined as ϕ=1 for completely wet and ϕ = 0 for completely dry.

The increase of the absolute humidity in airflow direction is given as

$$\frac{\partial \chi}{\partial z} = \frac{U \cdot w}{\rho_{ad} Q} = \frac{U \cdot \phi \cdot \rho_a \beta (m_w - m)}{\rho_{ad} Q} \tag{22}$$

where ρ_{ad}(kgDA/m³) is density of dry air. The relative humidity F and the degree of saturation Ψ in decimal number are defined as

$$\Phi = \Psi \frac{\chi_S + 0.622}{\chi + 0.622} \quad ; \quad \Psi = \frac{\chi}{\chi_S} \tag{23}$$

Practical Solution for Rock Surface Temperature

In order to develop a calculation system for airflow climate, the estimation method of the wet surface temperature becomes most important. Suppose a circular airway in radius R (m), θ (°C) is strata temperature, and λ (W/m°C) is thermal conductivity of strata around the airway, total heat flux transferred from wet surface into airflow q_W (W/m²) is equal to heat flux due to the strata temperature gradient perpendicular to the surface at the boundary, $r = R$.

$$\begin{aligned} q_W &= \lambda \left(\frac{\partial \theta}{\partial r} \right)_{r=R} = q_S + q_L \\ &= \alpha(\theta_w - \Theta) + \phi\, h_l \rho_a \beta \frac{\chi_S - \chi}{1 + \chi_S + \chi} \end{aligned} \tag{24}$$

where h_l (=2.50 x 10⁶-2370•θ_w) (J/kg) is latent heat for water evaporation. This relationship becomes the boundary condition at the surface for the fundamental equation that is used to decide the rock surface temperature, θ_w. Another boundary condition is expressed as $\theta = \theta_0$ at some far outer boundary in radius direction, where θ_0 (°C) is virgin rock temperature.

Two important non-dimensional numbers are Biot number, B_i ($= \alpha R / \lambda$), and Fourier number, κ ($= at/R^2$), where t(s) is the time since the airway was first ventilated, a($= \lambda / \rho\, Cp$)(m²/s) is thermal diffusivity of the strata (ρ (kg/m³) and Cp (J/kg°C) are density and specific heat of the strata).

Suppose η_t is the elapsed time factor, an approximated solution to predict θ_w for partly wet conditions has been proposed by authors (Sasaki et al., 1995). It is much simple and practical compared with previous methods, because θ_w can be calculated by only Eq.(25) without any iterative calculations.

$$\left.\begin{aligned} &\theta_w(\phi) = \frac{-\Delta_1 + \sqrt{\Delta_1{}^2 - 4\Delta_0 \Delta_2}}{2\Delta_0} \quad ; \quad \phi > 10^{-4} \\ &\theta_w = \Theta + \frac{B_i}{B_i + \eta_t}(\theta_0 - \Theta) = \theta_{wD} \ ; \quad 0 \le \phi < 10^{-4} \\ &\text{for } \Theta = 0 \text{ to } 32\ ^\circ\text{C}; \\ &\Delta_0 = 0.0467\phi \quad , \quad \Delta_1 = 1 + \eta_t / B_i + 0.436\phi \\ &\Delta_2 = 9.09\phi(1 - \chi/\chi_S) - (1 + 0.436\phi \cdot \chi/\chi_S)\Theta \\ &\qquad - 0.0467(\chi/\chi_S)\phi\Theta^2 - (\eta_t / B_i)\theta_0 \\ &\text{for } \Theta = 10 \text{ to } 40\ ^\circ\text{C}; \\ &\Delta_0 = 0.0873\phi \quad , \quad \Delta_1 = 1 + \eta_t / B_i - 1.11\phi \\ &\Delta_2 = 22.0\phi(1 - \chi/\chi_S) - (1 - 1.11\phi \cdot \chi/\chi_S)\Theta \\ &\qquad - 0.0873(\chi/\chi_S)\,\phi \cdot \Theta^2 - (\eta_t / B_i)\theta_0 \end{aligned}\right\} \tag{25}$$

where η_t has been presented for corresponding to the ranges of κ by Starfield et al. (1983) as

$$\left.\begin{aligned} &\kappa \le 1.5; \eta_t = \left[0.9879 + 0.3281(\ln\kappa) + 0.03064(\ln\kappa)^2\right]^{-1} \\ &1.5 < \kappa \le 10; \eta_t = \left[0.979813 + 0.373860(\ln\kappa)\right]^{-1} \\ &10 < \kappa \le 100; \eta_t = \left[0.839337 + 0.444718(\ln\kappa)\right]^{-1} \\ &100 < \kappa \le 1000; \eta_t = \left[0.683043 + 0.479054(\ln\kappa)\right]^{-1} \\ &\kappa > 1000; \eta_t = 2\Xi\left(1 - \Xi - \Xi^2 - \Xi^3\right)/0.57722 \\ &\qquad \Xi = 0.57722 / \left[(\ln 4\kappa) - 1.15444\right] \end{aligned}\right\} \tag{26}$$

However, the equation for $\kappa \le 1.5$ was expanded by authors (Sasaki et al., 1995). The solution to estimate θ_w is applicable to the range of Θ = 0~32°C or Θ = 10~40°C, practical ranges of χ, κ, B_i, ϕ, θ_0 and other rock thermal properties with differences less than 0.15°C to the results of Amano et al. (1980) using the finite difference method (Sasaki et al., 1995).

In present system, two types of wet surface models are able to be selected as expressing the mine condition.

a) Uniform wet surface model: The model is defined as a uniform wet condition in which difference between wet and dry parts is not clear. These wet conditions should be evaluated as the wetness ϕ kept a constant in a certain interval.

b) Partly wet surface model: The wet condition on the surface is consisted with completely wet and dry sections. Let wet area ratio be ϕ_a, average rock surface temperature be θ_w derived from linear summation as

$$\theta_w = \theta_{wD}(1 - \phi_a) + \theta_{wW} \tag{27}$$

where θ_{wD} and θ_{wW} are surface temperatures just for ϕ =0 (dry) and ϕ =1 (full wet) respectively.

The correction factors, which express the equivalent wetness ϕ instead of the wet area-ratio ϕ_a of partly wet surface, has been reported by authors. As their result, ϕ should be used as almost half value of ϕ_a to obtain almost same increases of airflow temperature and humidity (Sasaki, K. et al., 1995).

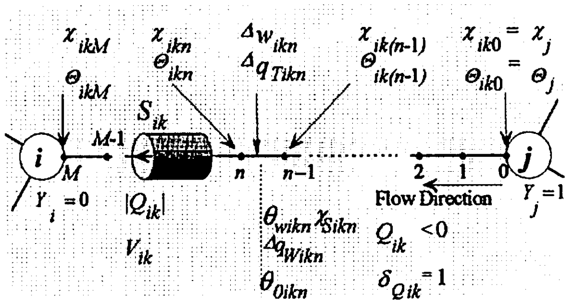

Figure 2. Schematic Airway Model for Climatic Condition.

Numerical Model for Network Airflow Climate

The temperature and humidity on nodes consisting of the recirculation circuit are calculated by introducing a function (indicator function Y_i) on node i, which indicate a degree of the progress of calculations on nodes, defined as

$$Y_i = \begin{cases} 0 & \text{; not deceided} \\ 1 & \text{; deceided tentatively(detect recirculation)} \\ 2 & \text{; already decided} \end{cases} \tag{28}$$

At the start of the calculation, while Θ, Ψ and so on at inlet nodes are given as the values equal to the atmospheric condition, i.e. $\Theta_\tau = \Theta_{IN}$, $\Psi_\tau = \Psi_{IN}$ and so on, the values of indicator function on inlets nodes, τ, are set as $\Psi_\tau = 2$. The airflow-conditions on other nodes are calculated from inlet nodes to downstream nodes, then the fan(outlet) nodes are calculated at last. However, the calculations at node *i* can be done only when the next conditions are completely satisfied for all airways connected to *i*.

$$Y_{J(i,k)} \neq 0 \ for \ Q_{ik} \leq 0 \ ; k = 1 \sim m(i) \tag{29}$$

Furthermore, before the calculations at the node, the change of airflow conditions upon the airway satisfying Eq. (29) are calculated from upstream to downstream. The climatic conditions are calculated by a kind of one dimensional difference methods by dividing the airway into 10 m in length based on Eqs. (21) and (22).

For a case of $\chi > \chi_s$ on the way, a numerical algorithm developed by Sasaki et al. (1992) has been used to correct both values of χ and Q little by little according to heat and mass balances, then total amount of excess water vapor is treated as condensate releasing latent heat. Especially, it is very effective for calculations in exhaust shafts which are influenced by auto-expansion with temperature reduction.

A symbolized thermal physical-property on node *i* defined as ξ_i such as Θ_i, χ_i and so on, is derived based on mass and heat balances at the node described as

$$\xi_i = \sum_{k=1}^{m(i)} \left(\delta_{Qik} \xi_{ikM} \rho_{ik} \left|Q_{ik}\right|\right) \Big/ \sum_{k=1}^{m(i)} \left(\delta_{Qik} \rho_{ik} \left|Q_{ik}\right|\right) \tag{30}$$

where ξ_{ikM} is the last calculation results of the airway flowed into the node *i* and δ_{Qik} is unit function indicating the flow direction (see Fig. 2) defined by

$$\delta_{Qik} = \begin{cases} 1 : Q_{ik} < 0 \\ 0 : Q_{ik} \geq 0 \end{cases} \tag{31}$$

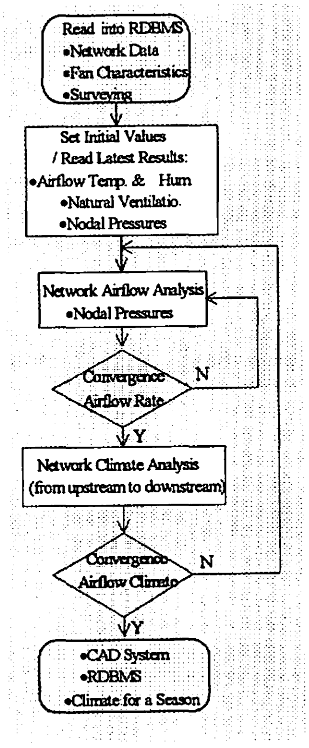

Figure 3. Analysis Flow Chart.

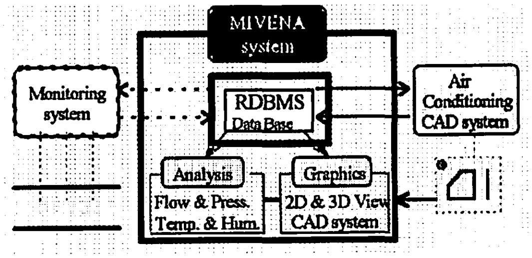

Figure 4. MIVENA System.

Continuing the calculation with Eq.(30), then whole properties related to airflow climate at all nodes are calculated and fixed at last.

For the case of $>_s$ in airflow after joining at a node, the calculation scheme for revisions of temperature and humidity (Sasaki et al., 1992) has been also adapted.

In order to get the final analytical results of both airflow quantities and climatic conditions, the iterative calculations for network airflow and climate are done alternately until the both convergence (see Fig. 3). After the annual calculations, the seasonal air flow temperatures are calculated with linear adding its change using the system proposed by Sasaki et al. (1992).

VENTILATION SIMULATOR "*MIVENA*"

The present analytical system have been successfully applied to a ventilation simulator named MIVENA run on the Microsoft Windows(NT)™ developed by authors since 1986. Figures 4 and 5 show the system windows consists of not only the analytical calculation systems, but the RDBMS, the 2D/3D graphic system, the CAD system for deformed network skeleton

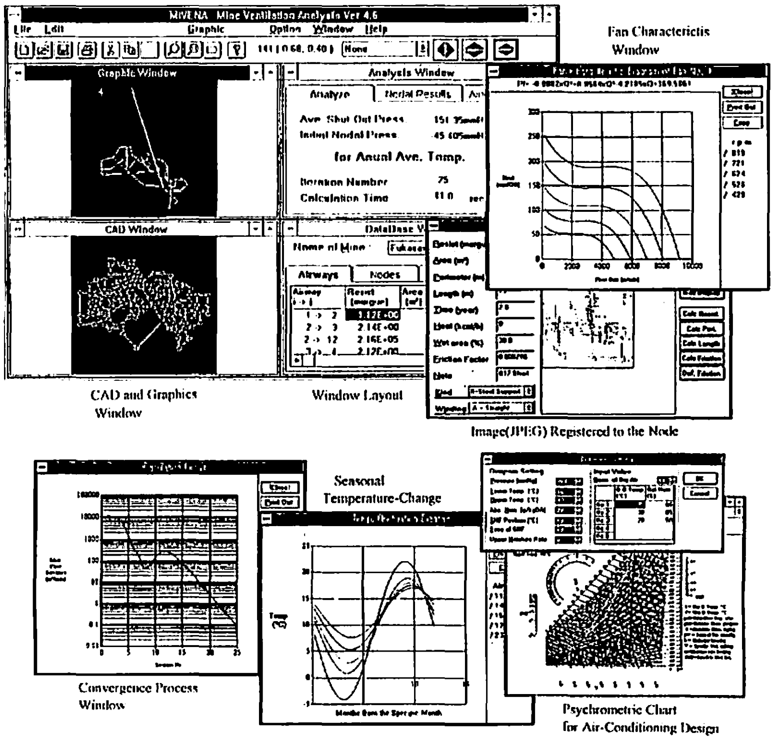

Figure 5. MIVENA's Windows.

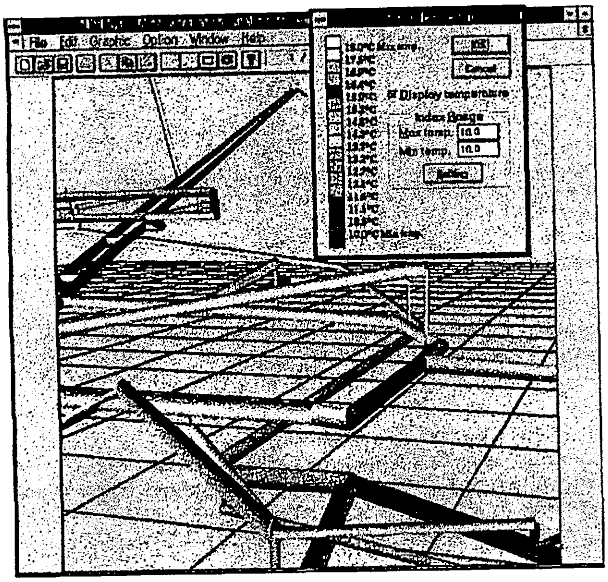

Figure 6. 3D-graphic System Using Open-GL (the Color Painted on Airway Surface is Showing the Airflow Temperature.)

Table 1. Comparison of Calculation Results of Dry Bulb Temperature for the Dry Airway.

Model/Code	t =3 months	t =3 years
CLIMSM*	31.47	30.20
Danko et. al.*	31.48	30.33
TUNNEL*	31.64	30.41
Mousset-Jones*	31.55	30.33
MIVENA	31.67	30.46

* : after Table 2 in Danko et al.(1988)
Analytical Conditions: z =500 m, Horizontal (ζ=0 rad)
U =12 m, S=9 m^2, (Δz =10 m was used in MIVENA)
λ=6.0 W/m°C, a =2.5×10^{-6} m/s^2, α =14.0 W/m^2
θ_0=45 °C , Θ_{IN}=28 °C , Φ_{IN}=0.782 (Ψ_{IN}=0.775)
Q=35 m^3/s, ρ_a =1.42 kg/m^3 , $\rho_{ad} Q$ =49.7 kg/s

and air-conditioning design system.

The 21,000 lines of programs have been written in MS Visual BASIC Ver. 3™ and Visual C++ Ver. 2™ (Open-G™ script was partly used, see Fig. 6).

The input and output data forms were designed in common with Windows™ applications, such as work-sheet data, text, HPGL™, Image pictures registered to the node/airway.

The RDBMS has been designed to have some convenient functions used to delete or add nodes and airways automatically by reevaluating $J(i,k)$ and $m(i)$. Those also have advantages to set up a data-base to describe the mine layout and solve network airflows for ventilation planning and design. Furthermore, a computer aided air-conditioning (cooling and heating) system has been developed to estimate airflow climate by using a displayed psychrometric chart based on the accurate equations for air conditions applicable to a very deep underground mine. Its ranges of pressure, temperature and humidity are specified by users.

RESULTS AND DISCUSSIONS

Table 2. Comparison of the Results Between Codes.

Model /Code	ϕ or ϕ_a (-)	Dry B. Temp. Θ(°C)	Wet B. Temp. Θ_{WB}(°C)
CLIMSM*	0.15	26.74	25.68
Danko et al.*	0.15	27.88	26.11
MIVENA	ϕ=0.15	27.64	25.65
TUNNEL*	0.15	29.38	25.74
MIVENA	ϕ_a=0.15	29.10	25.61

* : after Table 2 in Danko et al.[1988] , t=3 years
Analytical Conditions are same as that of Table 1

The calculation results for a single airway by the present system for airflow climate airway shows good agreement with the results of Uchino et al. (1982) using finite deference method (see Sasaki et al., 1995).

Danko et al. (1988) have suggested that the prediction results of mine climate by some computer codes are quite different for a case of partly wet condition. Then, the same configuration model reported by them has been calculated using the MIVENA system. The results are shown in Tables 1 and 2 comparing with ones of other calculation codes. From the results, it is pointed out that the difference between calculation results are very little for the dry airway, however that for partly wet condition is probably caused by the difference between wetness, ϕ and wet area-ratio, ϕ_a.

Placements of nodes in the networks analyzed were determined in consideration of airway junctions and types of the airways. The nodal numbers were manually given. The characteristic curves of its surface main fans illustrated in Fig. 5 is also inputted to the RDBMS.

With respect to the analyses of the actual networks of three copper mines (Ezuri,Fukasawa and Matsumine mines run by Hanaoka Mining Co. LTD., Akita, Japan), the solutions of Q_{ik} for the three mines agreed well with measured values within 18% of the total intake airflow-quantities. It should be noted that the uncertainty of the measurements was estimated to be more than 20% because the mines were running at the time of measurements. Furthermore, the MIVENA was successfully applied to construct the fan driving maps for main fans controlled with thyristors, which indicate the total inlet airflow-quantity on several seasons against the thyristor frequency, were made to find out its optimum frequency for each season.

CONCLUSIONS

A analytical system for underground ventilation simulators has been proposed. By introducing the connective function between nodes (Eq. (1)), the fundamental equations for the network airflow and climatic conditions are expressed in general forms fit to ventilation network analysis. It is not only convenient to manage ventilation data base and other graphical interface, but effective to save computer memory. The calculation system of the quasi-linear equations for the correction of nodal pressures as unknown variables using skyline modified Choleski's decomposition scheme has advantages on calculation speed and save of memory space as compared with the other schemes. The maximum absolute error in continuity of airflow quantity upon nodes is employed as the convergence criterion. The number of iterative calculations until convergence is less than 13 for the condition of constant fan pressure and airflow temperature. The calculation processing time is roughly in proportion to the total number of nodes to the 3/2 power.

The wet condition on underground airways is the most important factor to develop a prediction system for airflow climate and air-conditioning. The key part of the analysis is how to estimate the rock surface temperature upon airways with full or partly wet conditions. A new approximated solution to estimate the rock surface temperature has been provided. It is much simple and practical compared with previous methods or solutions because of simple equation without any iterative calculations. The solution is applicable to the range of airflow temperature from 0 to 32°C or 10 to 40°C and practical ranges of humidity, ventilation time, wetness and other rock thermal properties.

The airflow climatic conditions in the network are calculated by using a indicator function proposed which indicates approximation degree of the calculation result. The climatic conditions on nodes are calculated from inlet nodes to downstream nodes based on the indicator function, even if recirculation airflow circuits are existing. The climatic conditions of airflow in an airway flowed into the node are also calculated from upstream to downstream with a kind of one dimensional numerical difference methods by dividing the airways in 10 m in length before the calculations on the connected node.

The present analytical system proposed has been utilized with some success to predict the ventilation network airflow distributions and climatic conditions. Furthermore, the ventilation simulator named MIVENA system run on the Microsoft Windows™ has been developed by authors. The MIVENA system consists of not only the functions of analytical calculations but relational data base management system, 2D/3D graphic system, graphical network CAD system and air-conditioning design system adapting psychrometric chart correspond to any deep and hot underground mines using user-friendly interfaces.

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