FIELD-NETWORK MODEL FOR MINE FIRE SMOKE MOVEMENT[①]

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ABSTRACT To overcome the shortcomings of current mine fire simulation method, a new mathematical model, field-network model, was proposed for smoke movement simulation during mine fires. The model consists of field model, network model and proper boundary conditions. Field model is used in the fire source roadway, considering the large scale turbulent motion that controls the rate of diffusion of mass, momentum and heat. Network model is adopted in the other part of mine ventilation network to account for the complexity and integrity of the whole network. The new model absorbed the merits of economy and accuracy from both network model and field model. The solving method for the field-network model was also introduced.

Key words mine fire computer simulation field-network model

1 INTRODUCTION

At present most scholars at home and abroad are inclined to adopt one dimension unsteady model (network model) to simulate smoke movement during mine fires in their research work[1,2]. The method can roughly describle the overall effects of a fire that has exerted in a mine ventilation system. But in the simulation of the two or three dimensions phenomenon such as buck flow or back lush of fire smoke, especially smoke movement at early stage of a fire, the method is not effective, because in the initial period of a mine fire, the smoke is under the action of buoyancy and main fan pressure, the type of flow is reflux. Moreover, to survey the details of air conditions in local area, such as the smoke temperature distribution, smoke diffusion state, etc, in a limited area, the one dimension unsteady model is also unavailable.

Two or three dimensions model (field model) of a mine fire can meet the needs of fire smoke field simulation. Yet the solving process of this model has some shortages, such as more complicated system, larger computer memory and lower calculation rate, so using field model to simulate the whole mine ventilation network is more difficult, even infeasible to some degree.

In this paper, to overcome the shortcomings of the above models, a new mathematical model for smoke movement during mine fires field-network model, is established, and the solving method for the model is briefly introduced. The main ideas of the model are as fowllows:

(1) Making use of the accuracy of field model in solving complicate flow, the field model is adopted to the fire source roadway to accout for the complexity of turbulence and the properties of back flow.

(2) Taking advantages of the conciseness and practicability of network model in solving complicated network flow, the network model is used to the other part of the mine ventilation network to describle the overall circumstances of fire smoke movement in the whole network.

2 NETWORK MODEL FOR SMOKE MOVEMENT DURING MINE FIRES

In accordance with the features of the air flow in mine road during mine fires, to simplify

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the studied problem, certain hypotheses are made as follows:

(1) The air in mine road and the smoke from fires can be considered as multi-component ideal gas, the air and smoke obey the ideal gas equation of state.

(2) There are no chemical reactions happened during the smoke flowing in the roadway.

(3) The air flows drifted into a node of the network from several related branches are completely mixed before they drift out of the node, i. e. the flows from a node of the network have the same parameters.

(4) Resistent properties of the roadways and the ventilation installations (regulators, air door, air bridge etc.) are unchangeable.

(5) The temperature of roadway wall is equal to the temperature of the cooled zone in surrounding rock, the exothermic process to the roadway country rock of fire smoke can be considered as a heating process to the cooled zone, and the temperature of the roadway surface is an assumed constant.

(6) The diffusion of the poisonous or harmful gases in the roadway air flow is caused by the air turbulent mixture and convection.

According to the above hypotheses, on the basis of certain conservation laws and transport equation, one dimension unsteady differential equations describling the fire smoke movement, process of heat and mass transfer in mine ventilation network are set up.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0 \tag{1}$$

$$\frac{D\boldsymbol{V}}{Dt} = \boldsymbol{f} - \frac{1}{\rho}\nabla p - \frac{1}{\rho}\cdot\frac{\partial \sigma_u}{\partial L}\boldsymbol{e}_L \tag{2}$$

$$\frac{D}{Dt}\left(\frac{V^2}{2} + C_V T + gz\right) + \frac{1}{\rho}\cdot \frac{\partial}{\partial L}(pV) + \frac{1}{\rho}\frac{\partial \sigma_u}{\partial L}\cdot \boldsymbol{e}_L V = q \tag{3}$$

$$\frac{\partial C}{\partial t} + V\frac{\partial C}{\partial L} = K\frac{\partial^2 C}{\partial L^2} \tag{4}$$

$$C|_{t=0} = C(L, 0) \quad \text{(initial conditions)} \tag{5}$$

$$\sum Q_j C_j = 0 \quad \text{(boundary conditions)} \tag{6}$$

$$P_V = RT/\left(\sum_{i=1}^{n} \gamma_i M_i\right) \tag{7}$$

where ρ—air density; V—air flow velocity vector, $\boldsymbol{V} = V\boldsymbol{e}_L$; ∇—Hamiltonian operater, to one dimension flow, $\nabla = \boldsymbol{e}_L(\partial/\partial L)$; $\boldsymbol{e}_L$—the unit vector in the direction of air flow; D/Dt—particle derivation, suppose φ as a general variable, then, $D\varphi/Dt = (\partial\varphi/\partial t) + (\boldsymbol{V}\cdot\nabla)\varphi$; $\boldsymbol{f}$—volume force of unit mass, volume force is potential in the gravitational field, $\boldsymbol{f} = -\nabla u$, u—potential function, to the one dimension flow, $u = gz$, z is the roadway elevation, g is the acceleration of gravity; p—numerical value of the surface stress $\boldsymbol{P}_n$; σ_u—tangency stress of the air flow, i. e. the friction stress between the air flow and the roadway wall; $C_V T$—internal energy of the unit mass air flow; C_V—specific heat of constant volume of air flow; q—amount of heat exchanging between the air flow and the roadway country rock; C—concentration of the poisonous and harmful gases; K—mixing coefficient, $K = D_L + D_t + D_m$, under the condition of mine ventilation, $D_L \gg D_t \gg D_m$, so $K \approx D_L$; D_m—molecular diffusion coefficient; D_t—turbulent diffusion coefficient; D_L—convection dispersion coefficient; Q—air quantity in a mine road; j—the number of the branches connected to a node; R—general gas constant, $R = 8\,314$ J/kg·℃; r_i—volume concentraton of component gas i; M_i—molecular weight of component gas i.

The established network model is a group of complicated nonlinear differential equations, and difference method of characteristic curves is adopted to solve the model, by which the amount of calculation work is small, the stability of the difference format is well, and moreover the boundary conditions of the network nodes are easy to dispose. The concrete algorithm can be referred to some literatures[3,4].

3 FIELD MODEL FOR SMOKE MOVEMENT IN THE FIRE SOURCE ROAD

3.1 Governing equations

During mine fires, the flow of high temperature smoke in the fire source road is an unsteady process accompanied with heat and mass transfer. There are six dependent variables to describe this process, they are three velocity components (u, v, w), the pressure (p), the enthalpy (h)

or temperature(T), and gas concentration(C) etc. Under the hypotheses before, the transient conservation equations for the smoke flow in fire source roadway can be reached from the chemical hydromechanics equations, on this basis the Renoids time-average equations can be built , enclosing it with k-ε two-equation model, the governing equations for the field simulation of smoke movement in the fire source way can be obtained[5, 6]. There is a general form of the governing equations:

$$\frac{\partial}{\partial t}(\rho\varphi) + \mathrm{div}(\rho \boldsymbol{V}\varphi + \boldsymbol{J}_\varphi) = S_\varphi \qquad (8)$$

where φ—stands for the general variable; ρ, $\boldsymbol{V}$, $\boldsymbol{J}_\varphi$, and S_φ denote the air density, velocity vector, diffusive flux and source term respectively. The diffusive flux $\boldsymbol{J}_\varphi$ is given by

$$\boldsymbol{J}_\varphi = -\Gamma_\varphi \mathrm{grad}\,\varphi \qquad (9)$$

where Γ_φ—the effective diffusion coefficient of the general variable φ. Table 1 shows the meaning for terms in the governing equations.

The values of fire empirical constants in the turbulence model are assigned in Table 2.

3.2 Initial and boundary conditions

To complete mathematical analysis, proper initial and boundary conditions are needed, which includes inlet boundary, outlet boundary and solid boundary conditions etc.

(1) Initial conditions

The parameters of air flow in the mine road before a fire are used as the initial conditions, the initial values of k and ε are givern by Eqn. (10).

$$k_0 = 0.05 V_0^2,$$
$$\varepsilon_0 = C_D k_0^{3/2} / 0.03,$$
$$C_D = 1.0 \qquad (10)$$

(2) Boundary conditions

On the solid boundary of fire road, the non-slip condition is employed for the velocity components(u, v, w), their values are zero. For turbulence kinetic energy k, diffusive flux is zero on the wall. The turbulence kinetic dissipation rate ε is given by the wall-function[7, 8]. Suppose that the wall is of unpermeability to the smoke component, then $\partial C/\partial n|_w = 0$; the wall surface of the road is dry, and the temperature is assumed constant T_w.

Locally single-direction assumption is adopted at the outlet boundary[9], the longitudinal velocity at the outlet section can be calculated by Eqn. (11).

$$u_{L1,j} = u_{L2,j} + C' \qquad (11)$$

where C' is given by the law of mass conservation:

Table 1 Variables in general equation

Equation	φ	Γ_φ	S_φ
Density	1	0	0
x momentun	u	μ_{eff}	$-\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}(\mu_{\mathrm{eff}}\frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\mu_{\mathrm{eff}}\frac{\partial v}{\partial x}) + \frac{\partial}{\partial z}(\mu_{\mathrm{eff}}\frac{\partial w}{\partial x}) + (\rho - \rho_{\mathrm{ref}})g_x$
y momentun	v	μ_{eff}	$-\frac{\partial P}{\partial y} + \frac{\partial}{\partial y}(\mu_{\mathrm{eff}}\frac{\partial v}{\partial y}) + \frac{\partial}{\partial x}(\mu_{\mathrm{eff}}\frac{\partial u}{\partial y}) + \frac{\partial}{\partial z}(\mu_{\mathrm{eff}}\frac{\partial w}{\partial y}) + (\rho - \rho_{\mathrm{ref}})g_y$
z momentum	w	μ_{eff}	$-\frac{\partial P}{\partial z} + \frac{\partial}{\partial z}(\mu_{\mathrm{eff}}\frac{\partial w}{\partial z}) + \frac{\partial}{\partial x}(\mu_{\mathrm{eff}}\frac{\partial u}{\partial z}) + \frac{\partial}{\partial y}(\mu_{\mathrm{eff}}\frac{\partial v}{\partial z}) + (\rho - \rho_{\mathrm{ref}})g_z$
Enthalpy	h	$\mu_{\mathrm{eff}}/\sigma_h$	$-q_r$
Component	C	$\mu_{\mathrm{eff}}/\sigma_C$	0
k	k	$\mu_{\mathrm{eff}}/\sigma_k$	$G_k + G_b - \rho\varepsilon$
ε	ε	$\mu_{\mathrm{eff}}/\sigma_\varepsilon$	$\frac{\varepsilon}{k}[C_1(G_k + G_b) - C_2\rho\varepsilon]$

G_k—shear stress creation term, G_b—buoyancy creation term,
μ—viscosity coefficient, subscripts: t—turbulent,
l—laminar, b—buoyancy, ref—reference, eff—effective.

Table 2 Values of empirical constants

Constants	C_D	C_u	C_1	C_2	σ_k	σ_ε	σ_h	σ_c
Values	1.0	0.09	1.44	1.92	1.0	1.3	0.9	0.9

$$C' = [F_{in} - \sum_{j=2}^{M_2}(\rho_{L1,j})(u_{L2,j})A_j] / \sum_{j=2}^{M_2}(\rho_{L1,j})A_j \quad (12)$$

where $F_{\rm in}$ is mass flux at the inlet section of fire road, A_j is the area of the control volume (i, j) in y direction.

According to the locally single direction assumption, for variables h, C, k and ε, coefficient of difference equations a_E is zero at the outlet section.

SIMPLE algorithm is employed in this paper to solve the field model, the details of the algorithm can be referred to some documents[8, 9] and are not repeated here.

4 INTERFACE CONDITIONS AND NUMERICAL METHOD FOR FIELD-NETWORK MODEL

To commit united iteration solving for the the field-network model successively, the key problem is the right interface conditions to be given. At the place where the outlet of fire road is connected to the network, suppose the positive direction is pointed to network region, then the first control volume near the network in the field region is shown in Fig. 1.

The velocity u at the interface of the field and network area is

$$u = \frac{F_x^+}{\rho A_x} \quad (13)$$

$$F_x^+ = F_x^- + F_y^- - F_y^+ + F_z^- - F_z^+ - \frac{\partial \rho}{\partial t}\Delta V \quad (14)$$

where ΔV —volume of the control unit, A_x —area of the control unit in x direction.

The boundary conditions at the interface of field and network area are given as follows.

Considering the effects of network area on the field area, then:

(1) At the inlet of fire road

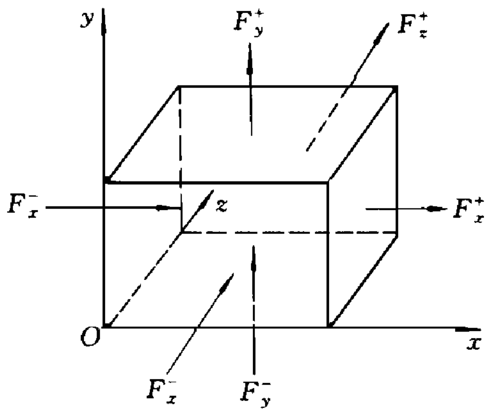

Fig. 1 Control volume at interface between field and network area

If $u > 0$, variables at the boundary are equal to values in the network area.

If $u < 0$, $\frac{\partial \varphi}{\partial x}|_{\rm inlet} = 0$, ($\varphi = u, v, w, h, C, k, \varepsilon$, etc.)

(2) At the outlet of fire road

If $u < 0$, variables at the boundary are equal to values in the network area.

If $u > 0$, $\frac{\partial \varphi}{\partial x}|_{\rm outlet} = 0$, ($\varphi = u, v, w, h, C, k, \varepsilon$, etc.)

As for pressure boundary condition of field area, the pressure in the network region is employed, and the pressure condition is given as following formula[10]:

$$p = p_n \exp(-\frac{\rho_r}{T_r}\frac{T_n}{p_r} gL) \quad (15)$$

where ρ_r, p_r, T_r —referential density, pressure and temperature, respectively; p_n, T_n —pressure, temperature in the network area respectively; L —position of the control volume.

When the effect of field area on the network area is considered, sums of parameters at the inlet or outlet boundary of fire road can be used as the boundary conditions of network area.

Field model and network model are coupled each other through the boundary conditions at the interface. Coupling iteration method should be employed on each time step to solve the field-network model. For a large and complicated mine ventilation network, the iteration time needed to solve the model is huge, so in this paper asynchronous iteration method is put forth to solve the model.

The movement of air in mine ventilation network is forced flow, the transfer rate of momentum is much bigger than the diffusion rate of temperature and concentration. So on each time step, the results of network analysis on the last time step are used as the interface conditions to solve the variables in field area on current time step, then use the results of field model analysis to solve the network region.

The solving procedure of field-network model is shown in Fig. 2.

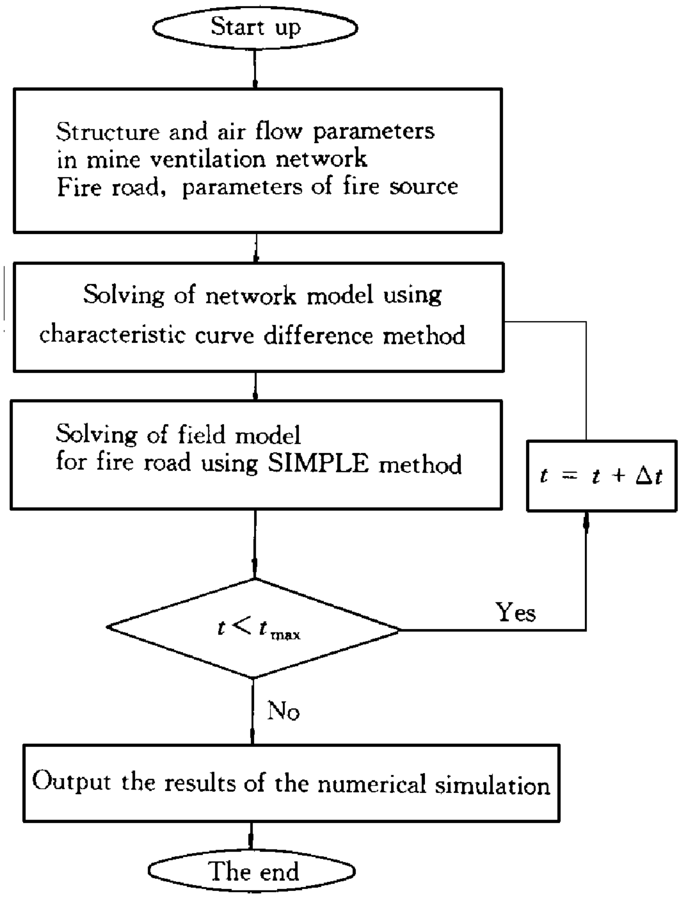

Fig. 2 Solving procedure of field-network model for smoke movement in mine ventilation network

In the solving of network model, the whole field area is considered as an imaging branch, the variables at the nodes of the imaging branch is the sums of parameters at the inlet and outlet boundary of field area.

5 CONCLUDING REMARKS

Field-network model absorbs the merits of both field model and network model, it is a development to the technique of mine fire computer simulation. Through simulation analysis, the model can not only account for the overall effect of a fire exerting on mine ventilation system, but also survey the details of smoke movement in fire road. This is of reference to the selection of evacuation routes for workers, positions for sensors detecting early fires and measures for air control.

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