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■ 기술보고 ■

Population Dose Assessment for Radiation Emergency in Complex Terrain

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• Abstract •

Gaussian plume model is used to assess environmental dose for abnormal radioactive release in nuclear facility, but there has a problem to use it for complex terrain. In this report, MATTEW and WIND04 Codes which had been verified were used to calculate wind field in the complex terrain. Under the base of these codes principle, wind fields were obtained from the calculation of the finite difference approximation for advection-diffusion equations which satisfy the mass-conservative law. Particle concentrations and external doses were calculated by using PIC model which approximate the particle to radioactive cloud, and atmospheric diffusion of the particles from the random walk method. The results show that the adjusted wind fields and the distributions of the exposure dose vary with the topography of the complex terrain.

1. INTRODUCTION

The environmental dose assessments due to the effluent cloud released from a nuclear facility to the atmosphere have been studying mostly with the Gaussian plume model [1].

In general, the Gaussian plume model is to use the solution of the diffusion equation that is acquired under the meteorological condition assumed the spatial homogeneity of the atmosphere disperse and the wind distribution. The concentration distribution of an effluent cloud in the Gaussian plume model is then given a normal distribution. If these assumptions are satisfied, the Gaussian plume model produces a fine result comparatively. The model applicate broadly as the result of merits discribing a detailed concentration distribution in vicinity of the release point and easing to perform mathematical operations [2].

In reality, however, neither the turbulance nor the released source strength is constant over long periods of time. Therefore, these properties can limit the practical application of the Gaussian plume model. There are many other models to compensate these limited properties, e.g.the trajectory-puff model, the segment model and the particle-in-cell (PIC) model.

In this paper, the PIC model was used. The adventages of the PIC model are as follows; the regional distributions for wind velocity can be handled simply, and each particle in a cell is able to get radioactivities, decay constants and coordinates. Basically, the PIC model solves the three-dimensional advection-diffusion equation in its flux conservative form for a non-divergent advection field by finite-difference approximation. It has been confirmed in ARAC system which was developed by LLNL and SPEED system which was developed by JAERI [3, 4].

The PIC model simulates the atmospheric dispersion by calculating the trajectories of many particles emitted from a particular point source. The concentration is determined by counting the number of paticle per unit volume [5, 6].

Schematic diagam of the relevant computer program is shown in Figure 1.

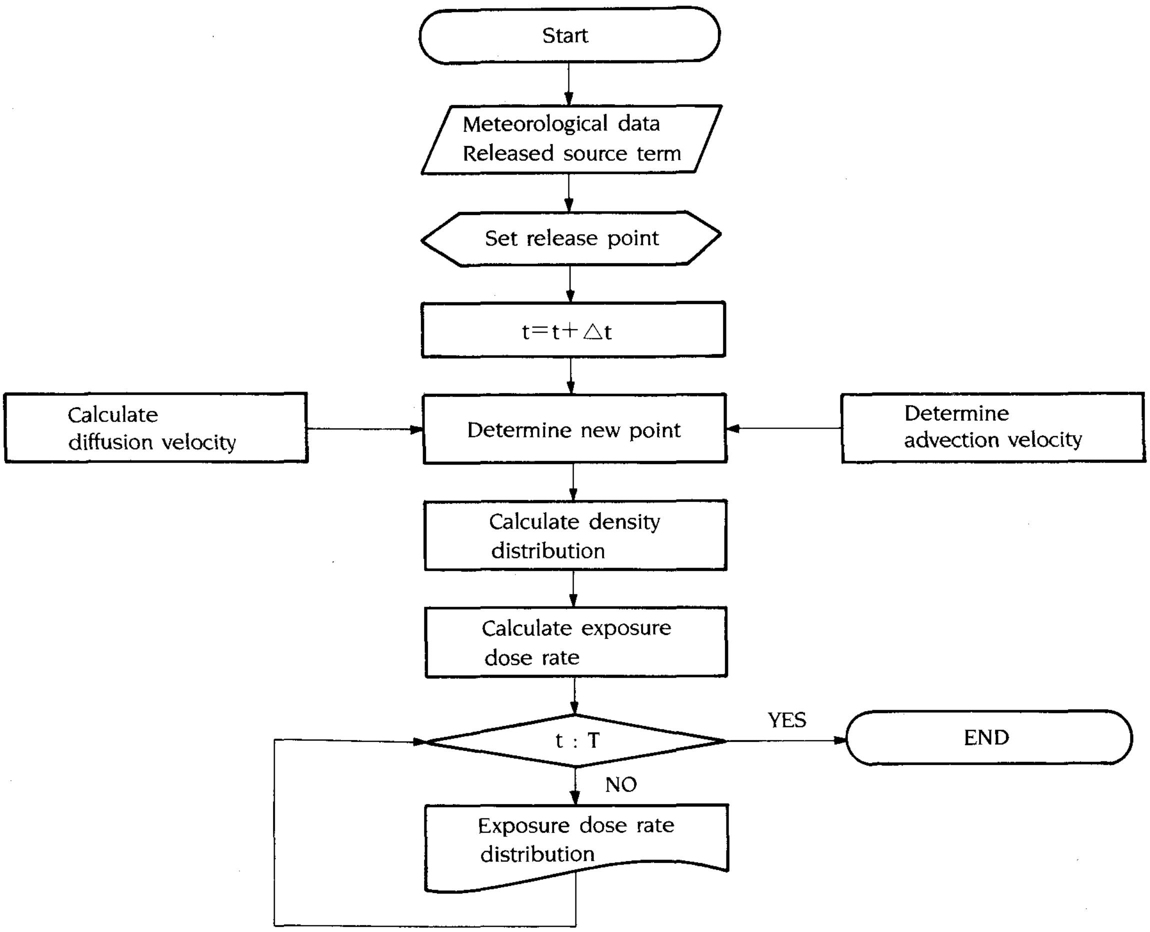


Fig. 1. Schematic diagram of the relevant computer program.

2. THEORY

1. Advection and diffusion of particles

The two approaches most commonly used to describe turbulant diffusion are the gradient transport theory and the statistical theory. The former deals with atmospheric transport at a fixed point while the latter tries to determine present diffusion from the statistical properties necessary.

In this paper, the gradient transport for transport-diffusion equation is used to simulate the atmospheric dispersion. The transport-diffusion equation is shown as follows [7].

$$\frac{\partial \chi}{\partial t}+U_A \cdot \nabla \chi - \nabla K \cdot \nabla \chi = 0 \quad \cdots\cdots (1)$$

where χ : scalar concentration

K : diffusion coefficent

U_A : mass consistent wind advection field

Under the assumption of imcompressibility, we can rewrite equation (1) in its flux conservative (pseudo velocity) form as follows [4, 5].

$$U_D = -K \cdot (\nabla \chi / \chi) \quad \cdots\cdots (2)$$

$$\frac{\partial \chi}{\partial t}+ \nabla[X \cdot (U_A U_D)] = \frac{\partial \chi}{\partial t} + \nabla(\chi \cdot U_P) = 0 \quad \cdots\cdots (3)$$

where U_P is the pseudo transport velocity.

A. Advection

Particles in a cell are transported by the wind velocity which is adjusted to satisfy the law of mass conservation. A difference functional is needed to minimize the deviation of the adjusted wind field from the observed field which subject to strong constraint that the adjusted field is non-divergent [8, 9].

The specific functional used in this study is

$$E(u, v, w, \lambda) = \int_V [\alpha_1^2(u-u^\circ)^2 + \alpha_1^2(v-v^\circ)^2 + \alpha_2^2(w-w^\circ)^2 + \lambda(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z})]\, dxdydz \quad \cdots\cdots (4)$$

where x, y: horizontal directions

z : vertical direction

$u^\circ, v^\circ, w^\circ$: corresponding observed variables

λ : Lagrange multiplier

α : Gauss precision moduli taken to be $\alpha^2 = 1/2\sigma^2$

σ : observation errors or deviations of the observed field from the desired adjusted field.

The equation for λ can be derived as fallows

$$\frac{\partial^2 \lambda}{\partial x^2}+\frac{\partial^2 \lambda}{\partial y^2}+\left(\frac{\alpha_1}{\alpha_2}\right)^2 \frac{\partial^2 \lambda}{\partial z^2} = -2\alpha_1^2\left(\frac{\partial u^\circ}{\partial x}+\frac{\partial v^\circ}{\partial y}+\frac{\partial w^\circ}{\partial z}\right) \quad \cdots\cdots (5)$$

$$u = u^\circ + \frac{1}{2\alpha_1^2}\frac{\partial \lambda}{\partial x} \quad \cdots\cdots (6)$$

$$v = v^\circ + \frac{1}{2\alpha_1^2}\frac{\partial \lambda}{\partial y} \quad \cdots\cdots (7)$$

$$w = w^\circ + \frac{1}{2\alpha_2^2}\frac{\partial \lambda}{\partial z} \quad \cdots\cdots (8)$$

By rewriting equation (5), the difference equation which is expanded to three-dimension is given by

$$\frac{\lambda_{i+1jk}-2\lambda_{ijk}+\lambda_{i-1jk}}{(\Delta x)^2}+\frac{\lambda_{ij+1k}-2\lambda_{ijk}+\lambda_{ij-1k}}{(\Delta y)^2} + \left(\frac{\alpha_1}{\alpha_2}\right)^2 \frac{\lambda_{ijk+1}-2\lambda_{ijk}+\lambda_{ijk-1}}{(\Delta z)^2} = D_o \quad \cdots\cdots (9)$$

$$D_o = -2\alpha_1^2\left(\frac{u^o_{i+1jk}-u^o_{ijk}}{\Delta x}+\frac{v^o_{ij+1k}-v^o_{ijk}}{\Delta y} + \frac{w^o_{ijk+1}-w^o_{ijk}}{\Delta z}\right)$$

Then, the adjusted wind components are as follows.

$$u_{ijk}=u^{o}_{ijk}+\frac{1}{2\alpha_1^2}\left(\frac{\lambda_{ijk}-\lambda_{i-1jk}}{\Delta x}\right)\cdots\cdots\cdots(10)$$

$$v_{ijk}=v^{o}_{ijk}+\frac{1}{2\alpha_1^2}\left(\frac{\lambda_{ijk}-\lambda_{ij-1k}}{\Delta y}\right)\cdots\cdots\cdots(11)$$

$$w_{ijk}=w^{o}_{ijk}+\frac{1}{2\alpha_2^2}\left(\frac{\lambda_{ijk}-\lambda_{ijk-1}}{\Delta z}\right)\cdots\cdots\cdots(12)$$

Equation (9) can be solved for residual R at each grid by successive over-relaxation method.

B. Diffusion

In a stochastic representation, particles are transported by the advection velocity while undergoing a series of random displacements simulating turbulant fluctuations. In one-dimensional diffusion phenomena, the probability distribution function $\rho(x, \Delta t)$ where a particle at the orgin will exist at x after time Δt, has following normal distribution [10].

$$\rho(x, \Delta t)=\frac{1}{2\sqrt{\pi K\Delta t}}\exp\left(-\frac{x^2}{4K\Delta t}\right)\cdots\cdots(13)$$

where diffusion coefficent K is defined by Pasquill [11].

Partieles are distributed with a standard deviation which is $\sqrt{2K\Delta t}$. After diffused for Δt, the transport distance x'_P of a particle P is

$$x'_P=[R]^{+\xi}_{-\xi}\cdots\cdots\cdots(14)$$

where $[R]^{+\xi}_{-\xi}$ is the random number between $-\xi$ and $+\xi$, and ξ is a function by which the standard deviation of x'_P becomes $\sqrt{2K\Delta t}$. The standard deviation σ_x is defined as fallow [4].

$$\sigma_x^2=\int^{+\xi}_{-\xi} P(x)\, x^2\, dx\cdots\cdots\cdots(15)$$

where P(x) is the probability density function.
So equation (14) can be written

$$x'_P=[R]^{+\sqrt{6K\Delta t}}_{-\sqrt{6K\Delta t}}\cdots\cdots\cdots(16)$$

$[R]^1_0$ is a random number between 0 and 1, and then

$$x'_P=\sqrt{24K\Delta t}\,(0.5-[R]^1_0)\cdots\cdots\cdots(17)$$

Because the horizontal diffusion parameter K_h is different from the vertical diffusion parameter K_v, the expessions for Y_p and Z_p becomes

$$y'_P=\sqrt{24K_h\Delta t}\,(0.5-[R]^1_0)\cdots\cdots\cdots(18)$$

$$z'_P=\sqrt{24K_v\Delta t}\,(0.5-[R]^1_0)\cdots\cdots\cdots(19)$$

Particle P which is transported by the wind field in a cell and diffused by equations (17), (18) and (19) moves to a new point x^*_P, y^*_P and z^*_P.

$$x^*_P=x_P+u\cdot\Delta t+x'_P\cdots\cdots\cdots(20)$$

$$y^*_P=y_P+v\cdot\Delta t+y'_P\cdots\cdots\cdots(21)$$

$$z^*_P=z_P+w\cdot\Delta t+z'_P\cdots\cdots\cdots(22)$$

2. Calculation of the density distribution

The average density per cell is obtained by counting the number of paricles in the cell. The density in the cell where the particles of number n existed during time step Δt A(i, j, k), is represented as

$$A(i,\ j,\ k)=\sum Q(P)\cdot\Delta t/V\cdots\cdots\cdots(23)$$

where V: volume of the cell

Q(P): radioactivity of a particle p.

Assuming the number of particles released during the time step t be N′, the radioactivity of a particle P is given as follows

$$Q(P)=(Q'\cdot\Delta t/N')\cdots\cdots\cdots(24)$$

where Q′: released ratio.

N′ may be calculated by

$$N'=(M_A/L_T)\cdot\Delta t\cdots\cdots\cdots(25)$$

where M_A: total number of particles released

L_T: release time.

3. Calculation of the exposure dose

The external exposure dose Dr (rem) during time $\triangle t$ at a surface point (x_o, y_o, 0) is a summation dose from each cell [10].

$$D_r(x_o, y_o, 0) = K_1 E_\gamma \mu_a \cdot \sum_{n=1}^{N}\left[\sum_{P=1}^{P_n} \frac{Q_{P,n}\ \exp(-\mu r_{P,n})}{4\pi r^2} B(\mu r_{P,n})\right] \triangle t \cdots\cdots(26)$$

where
- K_1: Conversion parameter for the exposure dose
- E_γ: γ energy
- μ_a: absorption coefficent of air
- N: number of step
- P_n: number of existing particles in step n
- $Q_{P,n}$: radioactivity of particle P in step n
- μ: attenuation coefficent of air
- $r_{P,n}$: length from a cell to a evaluation point
- t: time duration of step n
- $B(\mu r_{P,n})$: build-up factor of air.

3. CALCULATING CONDITION

1. Cell

SPEED system is divided into 3 types of cell; advection cell, diffusion cell and concentration cell [4], but ADPIC uses one cell to calulate advection, diffusion and concentration [5]. In case of radiation emergency in a nuclear facility, the real time assessment is an important factor to establish a emergency counter plan. In this sense, it would be desirable for rapidity and certain accuracy to calculate advection, diffusion and concentration with one cell which represent a definite space.

In this paper, one cell is used to calculate advection, diffusion and concentration. The cell sizes 250m×25m×25m and 40×40×20 in numbers. The concetration in a cell is represented by the number of particeles in the cell.

2. Calculation data and condition

The released radioactive material is assumed to release 3, 000 particles per 30 seconds. Also, it is assumed that the wind direction be south, the height of meteorological observation 75m, the effective stack height 225m and the release rate 1.2 Ci/h.

Boundary conditions are two types, $\lambda=0$ and $\partial\lambda/\partial n=0$. When λ is zero on a boundary, the amount of mass entering or leaving the volume is changed. Therefore, the adjustment for the vertical wind component in a boundary is permitted, but adjustment for the vertical wind component is not permitted. If the variation of the normal velocity component is zero on the boundary, the adjusted value of the normal velocity must be the observed value.

In the wind field calculation, the boundary conditions of the interested volume are $\lambda=0$ at the upper boundary, $\partial\lambda/\partial n=O$ in the inside boundary.

4. RESILTS AND DISCUSSION

1. Wind field calculation

First of all, a simple topography as Figure 2 with 10km×6km×250m was used to verify the relation between the weighting factor ω and the accuracy in the wind field calculation. It was assumed that the height of the mountain was 175m, the number of cell 20×12×10 and the size of each cell 500m×500m×25m. In addition, the wind speed was 5 m/sec, the wind direction east, and a limit value of the convergent 1×10^{-4}.

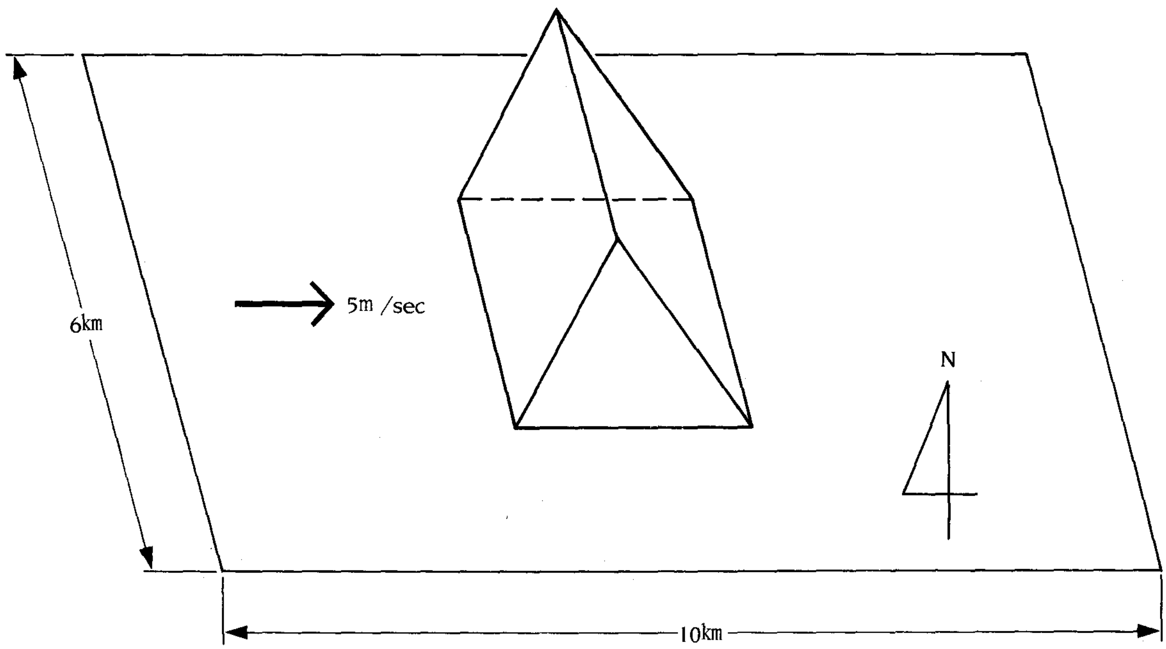


Fig. 2. Schematic drawing of the model topography.

The calculated results under the above conditions are shown in Figure 3. Figure 3 is a plane section taken along the predominated flow at the height of 125m. We can see that a stream of air flows round the outside of the mountain.

In using the successive over-relaxation method, the value of weighting factor ω is assigned between 1.0 and 2.0. The lower the value of ω is, the slower the convergence is. Figure 3 is the result for ω=1.7.

2. Calculation of the exposure dose

The distribution of the total body exposure dose was calculated using the topography as Figure 4. Wind direction is south, wind speed 4m/sec and atmospheric stability C.

Figures 5 and 6 show the distribution of the total body exposure dose at groud surface in 15 minutes after the release. The distribution of exposure dose for which the effects of the topogra-

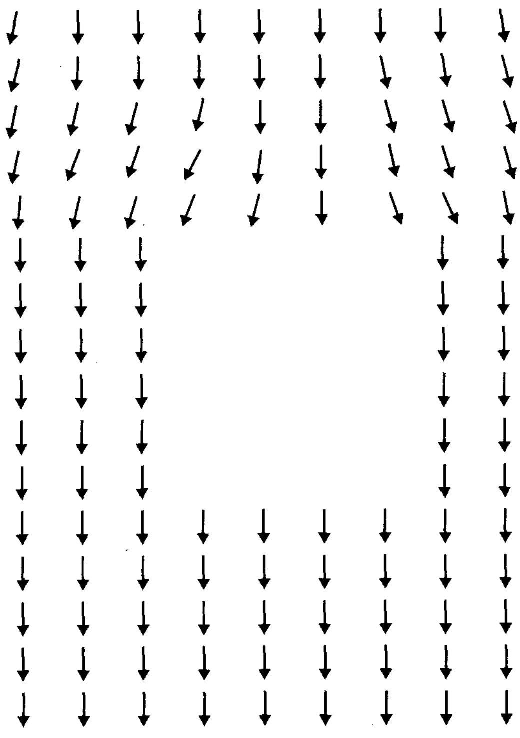


Fig. 3. Adjusted wind field. (Horizontal wind field of 125m)

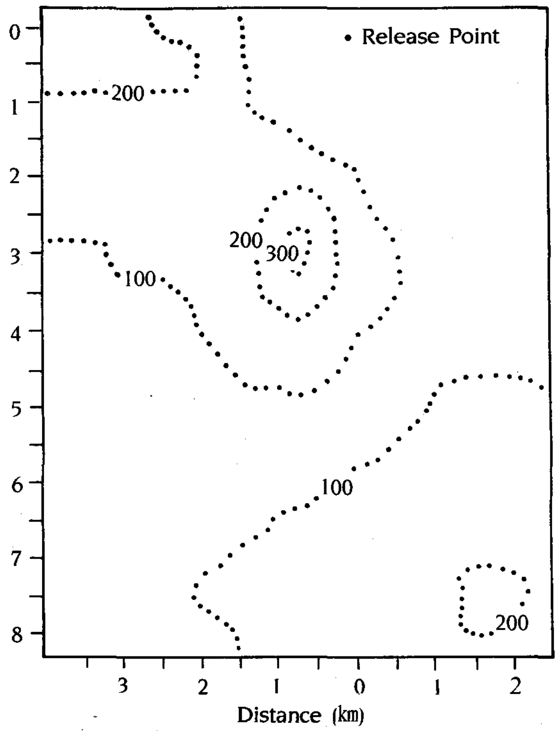


Fig. 4. Topography of calculated area

phy is not considered is showr in Figure 5. The distributions locates on the main axis of wind direction. As expected, the contour in Figure 6 which represent the distribution of exposure dose under the effects of the topography shifted to the edge of the mountain.

5. CONCULSION

In this paper, a dose assessment which includes interpretation of the wind field, random walk method for the atmosperic diffusion and PIC model for the dose assessment, is introduced.

The calculated wind field which retlects the physical constraint of mass conservation and the distribution of exposure dose which is calculated by the modified wind field represent the topograpic effect well. It needs to do the diffusion experiment in order to assess whether the numerical model fits the real dispersion.

The cell size must be determined according to the condition of assessment. Large cell reduces the time of calculation while errors in the calculated results increase. It is better to determine the cell size by analyzing the results calculated by changed conditions.

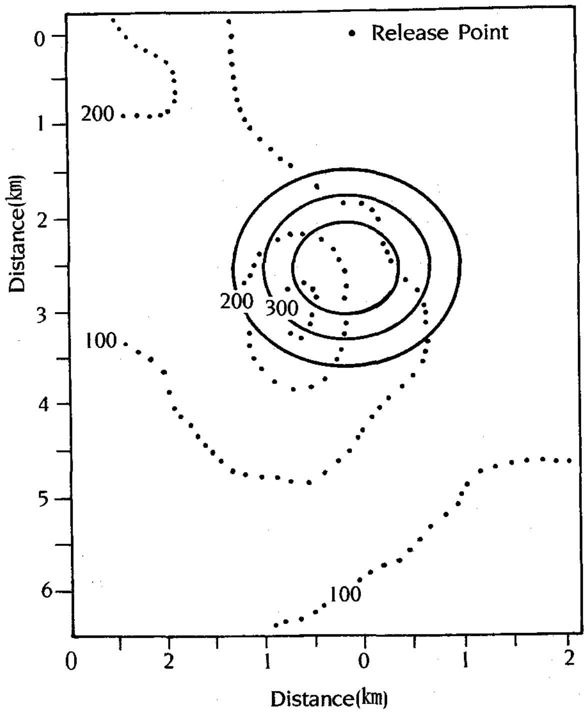
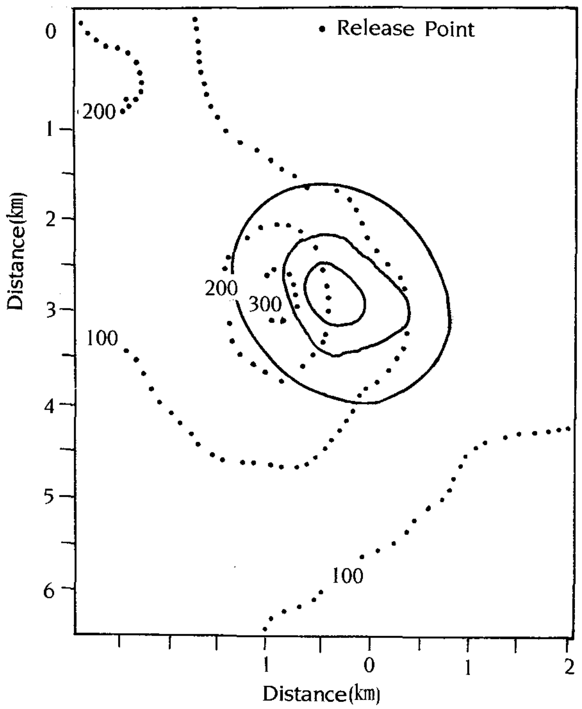


Fig. 5. Calculated exposure dose rate distribution (15 min) by using Gaussian plume model.



Contour values from inside
: 0.5 R/h 0.05 R/h 0.005 R/h

Fig. 6. Calculated exposure dose rate distribution (15 min) by using three-dimensional wind field.

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복잡 지형에서의 주민선량 계산

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● 요 약 ●

원자력 시설에서 대기중으로 방출되는 방사성 구름에 의한 환경선량계산에는 Gaussian plume model이 주로 사용되고 있으나, 바람의 분포나 대기의 흐트러짐이 공간적으로 일정하지 않은 복잡 지형에의 적용에는 문제가 있다.

복잡 지형을 고려한 기류계산에는 MATTEW, WIND04 코드가 그 타당성을 인정받고 있다.

이러한 코드의 원리를 기초로 하여, 질량보존법칙을 만족하는 이류 확산 방정식을 유한차분법으로 계산하고 풍속장을 구하였다.

입자 농도와 피폭선량은 방사성 구름을 입자군으로 근사시키는 PIC model을 이용하여 계산하였으며, 입자의 대기 확산은 Random Walk법을 이용하였다.

계산 결과, 지형에 의한 풍속, 풍향의 변화를 알 수 있었으며, 피폭선량분포를 구할 수 있었다.