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Estimation of external plume dose for a coastal site

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ABSTRACT

Estimation of external exposure due to atmospheric releases of photon emitting radionuclides from nuclear facilities is important during normal and emergency conditions since their contribution to the total public dose is relatively significant. Gaussian plume model coupled with either semi-infinite cloud model or finite plume integration method is normally used to estimate this dose component for inland sites. However, for coastal sites, shoreline dispersion model that handles local sea-land breeze circulation should be coupled with the external plume dose-computing module. In the present study, plume external photon dose is calculated for coastal sites considering appropriate combination of these two dispersion models and finite plume integration model. Based on this methodology, a simple and fast calculation tool is developed to estimate external plume doses under normal operating (sector average plume) and accidental conditions (single plume). This numerical program can also be used for source term estimation from field measurements, thereby assisting decision support system during emergency situations.

1. Introduction

External exposure from radioactive plume is the most important exposure pathway during the initial or early phase of a nuclear accident. Eulerian or Lagrangian dispersion simulations driven by mesoscale numerical weather prediction models provide more realistic estimates of the dose rates (Lyons et al., 1995; De Tomasi et al., 2011); however, present study focuses on developing a simple and fast response tool with small computational cost using Gaussian plume model. Rapid estimation of this external dose rate is usually carried out using semi-infinite cloud model in which a person is submerged in a radioactive cloud of infinite extent with uniform Ground Level Concentration (GLC). However, the semi-infinite cloud approximation fails when stable meteorological conditions prevail in the atmosphere for elevated releases and shorter downwind distances (nearer to the release location). Hence, preferably the external exposure should be obtained by integrating the point kernel response over the entire Gaussian plume or puff at the given receptor locations (finite cloud integration method). Many studies are carried out with the combination of Gaussian Plume Model (GPM) and finite cloud integration method in the past to estimate external exposure for inland sites (Overcamp and Fjeld, 1987; Gorshkov et al., 1994; Wang et al., 2004; Pecha Petr and Pechova, 2014); nomograms and look-up tables are prepared for various input parameters (Lahti et al., 1981, 1982; Hukkoo et al., 1988), and interpolative methods are used for plume photon doses at inland sites. However, very few studies are available that evaluate external plume exposure for coastal sites, except for one that uses semi-infinite cloud model (Srinivas and Venkatesan, 2005). In the present study, an attempt has been made to estimate plume doses for coastal sites using finite cloud integration method taking into account plume dispersion in a shoreline environment.

Coastal sites vary from inland environments in several ways (ex. temperature and roughness), which affect the dispersion of radionuclides (Kumar and Thomas, 1985). An internal boundary layer forms whenever the airflow crosses a discontinuity in surface temperature between the land and sea. The internal boundary layer due to the roughness difference by the effects of the thermal discontinuity is generally known as Thermal Internal Boundary Layer (TIBL), and it grows with downwind distance until it reaches the inland mixing layer height. Plume fumigation results when a plume emitted from a tall stack drifts from colder sea region to heated land; initially, the plume travels with relatively little dispersion in the stable layer and intersects the TIBL at a certain downwind distance (DiCristofaro and Touma, 1992). As long as this condition exists, fumigation may occur continuously and result in a high GLC. A multipoint Gaussian dispersion model, termed as Shoreline Dispersion Model (SDM), handles this unique meteorological phenomenon in the shoreline environment to determine GLC from tall stationary point sources (Van Dop et al., 1979; Misra, 1980).

In the present work, we handle the pollutant dispersion in the stable

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and unstable layers by GPM and SDM respectively to determine the airborne radionuclide concentration and couple it with finite plume integration module to estimate the external plume dose for a coastal site. This is due to the fact that in case of an elevated release, plume dose component from the stable region contributes significantly at short downwind distances although GLC is insignificant, and coastal fumigation effects increase GLC at long downwind distances. A numerical program is developed to implement this approach and the results are further discussed.

2. Method

Gaussian plume model is widely used to calculate the concentration of radionuclides at any receptor location, released from inland facility and is given by Eqs. (1a) and (1b), corresponding to the single plume and sector average plume concentration respectively. Eq. (1a) is used in estimation of concentration under instantaneous accidental release conditions while Eq. (1b) is used to estimate concentration under normal releases during changing meteorological conditions.

$$\chi(x,y,z) = \frac{\dot{Q}}{2\pi\sigma_y(x)\sigma_z(x)U_L} exp\left(-\frac{y^2}{2\sigma_y^2(x)}\right)\left[exp\left(-\frac{(z-H)^2}{2\sigma_z^2(x)}\right) + exp\left(-\frac{(z+H)^2}{2\sigma_z^2(x)}\right)\right] \tag{1a}$$

$$\chi_{ij}(x,z) = \frac{\dot{Q}}{\sqrt{2\pi}x\theta}\sum_k \frac{N_{ijk}}{U_k\sigma_{z_i}(x)}\left[exp\left(-\frac{(z-H)^2}{2\sigma_{z_i}^2(x)}\right) + exp\left(-\frac{(z+H)^2}{2\sigma_{z_i}^2(x)}\right)\right] \tag{1b}$$

where $\chi(x,y,z)$ is the radionuclide concentration (Bq m^{-3}) at x,y,z coordinates of the receptor location, $\dot{Q}$ is the release rate of the pollutants (Bq s^{-1}), σ_y,σ_z are the dispersion coefficients for the horizontal and vertical directions (m) either from Pasquill-Gifford (PG) or Briggs parameterization, U_L is the mean wind speed at the release height (m s^{-1}), and H is the release height (m), N_{ijk} is the number of hours for the given stability class i, wind direction sector j, and wind speed class k, θ is width of the sector (22.5°).

In the case of land-water interface regions such as coastal sites, the approach used for inland sites is modified to account for fumigation correction due to formation of TIBL in the atmosphere (Fig. 1). Initially, the radioactive plume released into the environment through stack disperses in the stable layer above the TIBL. After a certain downwind distance, the plume interacts with TIBL and the radionuclides are entrained inside the TIBL. Once entrained in the TIBL, the radioactive pollutants uniformly mix along the vertical direction. The inventory of radionuclides trapped inside TIBL depends on concentration of radionuclides within the stable layer, diffusion of radionuclides and the rate of formation of TIBL. The diffusion through TIBL surface depends on spread of the plume in the stable layer (σ_z), which is given by GPM. The ground level concentration within TIBL (unstable layer as shown in Fig. 1) is then given by SDM (Misra, 1980) as,

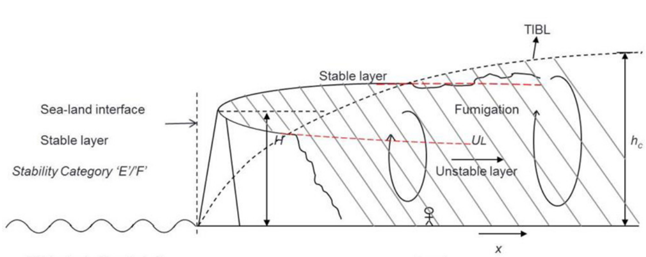

Fig. 1. Schematic diagram of plume dispersion in a typical coastal region.

$$\chi(x,y) = \frac{\dot{Q}}{2\pi U_L h(x)}\int_0^x \frac{1}{\sigma_{yf}(x')} exp\left\{-\frac{(h(x')-H)^2}{2\sigma_{zs}^2(x')} - \frac{y^2}{2\sigma_{yf}^2(x')}\right\}\frac{d}{dx'}\left(\frac{h(x')-H}{\sigma_{zs}(x')}\right)dx' \tag{2}$$

where $\sigma_{yf}(x')$ is effective dispersion coefficient of plume along crosswind horizontal direction inside TIBL given by, $\sigma_{yf}(x') = \sqrt{\sigma_{ys}^2(x') + \sigma_{yl}^2(x')}$, σ_{ys} is the dispersion coefficient of pollutants along the crosswind horizontal direction over the stable layer (sea) whereas $\sigma_{yl}(x')$ is the dispersion coefficient of plume in crosswind horizontal direction inside TIBL (land), $\sigma_{zs}(x)$ is the vertical standard deviation of position of particle at a distance x after release from the stack. The concentration at any point inside TIBL is given by integrating Eq. (2) numerically. The TIBL height (Misra, 1980) is given by:

$$h(x) = \left(\frac{2H_0 x}{\rho C_p \frac{d\varphi}{dz} U_L}\right)^{\frac{1}{2}} = A\sqrt{x} \tag{3}$$

where $A = \left(\frac{2H_0}{\rho\, C_p \frac{d\varphi}{dz} U_L}\right)^{\frac{1}{2}}$, H_0 is surface sensible heat flux (W m^{-2}), x is downwind distance (m), C_p is specific heat at constant pressure (J kg^{-1} per °C), $\left(\frac{d\varphi}{dz}\right)$ is the potential temperature gradient (°C m^{-1}). TIBL height depends on the site and meteorological parameters, which can be evaluated from the experimental data. It changes during the daytime depending on the value of coefficient A.

Using the radionuclide concentration in the plume (Eqs. (1) and (2)), the photon flux at any receptor location (x, y, z) is estimated using point kernel integration technique (Healy, 1984; Shultis and Faw, 2010) as shown below. The photon flux is then converted to dose rate using appropriate dose conversion factors. The integration of point kernel response of external plume source to obtain dose rate at any downwind distance (receptor location) is then given by,

$$\dot{D} = \alpha E_\gamma \frac{\mu_a}{\rho}\int\int\int \frac{B(\mu r)}{4\pi r} exp(-\mu r)\chi(x,y,z)dx\ dy\ dz \tag{4}$$

where $r = \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2}$, is the distance of the receptor from the source location (m), E_γ is the energy of the photon (MeV), μ_a is the linear energy absorption coefficient (m^{-1}) defined as fraction of energy lost per unit length of the medium, ρ is the air density (1.1 kg m^{-3}), μ is the linear attenuation coefficient (m^{-1}) defined as fraction of photons removed from the incident flux per unit length of the medium, $\chi(x,y,z)$ is the radionuclide concentration (Bq m^{-3}), $B(\mu r)$ is the buildup factor having no dimensions, α ($1.6{*}10^{-13}{*}3600 = 5.8{*}10^{-10}$) is the MeV s^{-1} to J h^{-1} conversion factor, and $\dot{D}$ is the dose rate in the air medium (Sv h^{-1}). In the present study, linear form of build-up is used. However, more accurate approximations for build-up shall be used for photons of energies around 0.1 MeV (Raza and Avila, 2005).

Using Eq. (4), the dose rate is calculated by integrating over the entire plume i.e. the contribution of plume in the stable layer above TIBL given by GPM (Eq. (1a)) and inside TIBL governed by SDM (Eqs. (2) and (3)). This combination of dose evaluation modules is referred to as Shoreline Gaussian Plume Exposure Model (SGPEM) in this study, which is implemented in a numerical program by integrating Eq. (4) using 64-point Gauss quadrature technique for any receptor location. Although the integration limits can extend from $-\infty$ to $+\infty$ along y-axis and 0 to $+\infty$ along z-axis as seen from Eq. (4), they are limited to 5 times the mean free path (which is a function of photon energy and medium of travel) of the photon in air (Wang et al., 2004). A parallel version of this numerical program is developed using Message Passing Interface (MPI) to make optimum use of available hardware resources for multiple calculations, thereby reducing computation time. This parallel program will be very valuable when the release contains multiple radionuclides that decay with copious energies.