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Effect of raindrop size distribution on scavenging of aerosol particles from Gaussian air pollution plumes and puffs in turbulent atmosphere

*Tov Elperin**, *Andrew Fominykh*, *Boris Krasovitov*

Department of Mechanical Engineering, The Pearlstone Center for Aeronautical Engineering Studies, Ben-Gurion University of the Negev, P.O. B. 653, 84105 Beer-Sheva, Israel

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ABSTRACT

We obtained exact analytical solution of advection–diffusion equation assuming turbulence parameterization for Gaussian pollution dispersion and taking into account scavenging of aerosol particles by rain. The effect of raindrops size distribution was taken into account by using Monte Carlo simulations whereby we assumed the log-normal size distribution of raindrops with Feingold and Levin parameterization. The developed approach allows analyzing spatial and temporal evolution of aerosol concentration in the gaseous phase as well as in the raindrops. We derived explicit analytical expression which allows analyzing the dependence of the rate of the below-cloud aerosols scavenging from Gaussian air pollution plumes on different parameters, e.g. rain intensity, pollutant emission rate, droplet size distribution. It is found that maximum ground level concentration of aerosols depends on rainfall intensity, and the location of the maximum approaches the emission source when rainfall intensity increases. Comparison of predictions of theoretical model with experimental data available in the literature showed fairly good agreement between theoretical results and experiments. The obtained results can be useful in the analysis of different meteorology–chemistry models including scavenging of aerosols in air pollution plumes by rain and for the assessment of human exposure to various chemical, biological and radiological contaminants.

1. Introduction

The Earth's atmosphere contains variety of aerosols emitted from various natural and anthropogenic sources such as factory stacks, fires, volcanoes, etc. Although it is commonly accepted that air pollution is dominated by local emissions many studies report that plumes of harmful pollutants can be transported by wind across oceans and continents and warn about the growing danger of air quality degradation (Ewing et al., 2010; Stith et al., 2009). The International Agency for Research on Cancer (IARC) evaluation showed an increasing risk for a wide range of diseases, e.g. lung cancer, respiratory and heart diseases, with increasing levels of exposure to particulate matter and air pollution (IARC, 2013).

Large amount of aerosols is involved in cloud formation and below cloud rain scavenging processes (Levin and Cotton, 2009; Chate et al., 2011). Precipitation scavenging is assorted as rainout (i.e. particles serving as cloud condensation nuclei); and as washout (i.e. scavenging of particles located below cloud base by falling raindrops, see e.g. Seinfeld and Pandis, 2006). Sutton (1932) derived the following formula for pollutant concentration distribution from a continuous point source

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* *Corresponding author*. Tel.: +972 8 6477078; fax: +972 8 6472813.
E-mail addresses: elperin@bgu.ac.il (T. Elperin), fominykh@bgu.ac.il (A. Fominykh), borisk@bgu.ac.il (B. Krasovitov).

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List of symbols

a, b	coefficients depending on stability class and distance from the emission source (see Eq. (30))
c	concentration of aerosol particles
C_y, C_z	average turbulent diffusion coefficients
C_c	slip correction factor
d_p	diameter of aerosol particle
D_d	diameter of the rain droplet
E	collision efficiency
H	effective stack height or emission height
I	rainfall intensity
J	mass flux
$\mathbf{K}$	eddy diffusivity tensor
Kn	Knudsen number
n	function of wind velocity and the vertical coordinate (see Eq. (2))
$N_d(D_d, t)$	raindrop number density distribution
p	loss constant
Q	pollutant emission rate
Re	Reynolds number
r_g	ground reflection coefficient
S	rate of scavenging of aerosol particles
S^*	critical Stokes number
Sc	Schmidt number
St	Stokes number
t	time
$\bar{u}$	mean wind velocity
U_t	rain droplet terminal velocity
u_t	particle terminal velocity
x	downwind coordinate
y	crosswind coordinate
z	vertical coordinate

Greek symbols

α, β	coefficients depending on stability class and distance from the emission source (see Eq. (30))
Λ	scavenging coefficient
ρ	density
μ	viscosity
σ_x, σ_y, σ_z	dispersion parameters

Subscripts

A	advective
a	air
D	diffusive
d	droplet
p	particle
t	terminal
w	water

located at $x = y = z = 0$ and assuming the reflection symmetry with respect to the plane $z = 0$:

$$c = \frac{2Q}{\pi C_y C_z \bar{u} x^{2-n}} \exp\left\{ -x^{n-2} \left(\frac{y^2}{C_y^2} + \frac{z^2}{C_z^2} \right) \right\}, \tag{1}$$

where x, y, and z are downwind, crosswind and vertical coordinates, respectively, c is the concentration, $\bar{u}$ is the mean wind velocity, Q is the emission rate, C_y and C_z are average turbulent diffusion coefficients in the crosswind and vertical directions. The exponent n in Eq. (1) is a function of wind velocity and the vertical coordinate:

$$\frac{\bar{u}}{\bar{u}_1} = \left(\frac{z}{z_1} \right)^{n/(2-n)}, \tag{2}$$

where the parameter n varies from 0 to 1. It must be emphasized that Eqs. (1) and (2) are unsuitable for predicting exact values of concentration for a wide range of meteorological conditions because of difficulties in determining the coefficients C_y, C_z and n. During the past several decades a number of studies used Gaussian plume-based diffusion models to predict the downwind concentration of air pollutants emitted from emission sources such as industrial plants, fires, volcanoes, etc. Releases of short duration can result from safety valves disc ruptures, sudden failures of storage tanks, reactors, lines, etc. Palazzi et al. (1982) suggested a simple model of diffusion of substances emitted during short duration releases into an infinite mixing layer. Mikkelsen et al. (1987) proposed a statistical model for turbulent diffusion of the instantaneously released puff whereby relative displacement of fluid particles is described by Gaussian stochastic process. Bianconi and Tamponi (1993) derived analytical solution to the non-stationary advection–diffusion equation of substances subjected to chemical–physical decay in a finite mixing layer for releases of short duration. This solution is suitable for describing spread of hazardous pollutants after accidental releases of toxic, flammable or explosive substances.

Atmospheric dispersion modeling refers to the mathematical description of contaminant transport in the atmosphere. The term dispersion is used to describe the combination of diffusion (due to turbulent eddy motion) and advection (due to wind) that occurs within the air near the Earth's surface (Stockie, 2011). The primary inputs to a dispersion model are pollution emission rate, meteorological data, receptor information etc. The output from the model is the downwind concentration of air pollutants emitted from emission source. Based on the Gaussian approach, different air pollutant dispersion models, algorithms and computer codes have been developed. A steady state Gaussian algorithm, that is applicable to urban areas for pollutants emitted from the point and area sources, was suggested by Novak and Turner (1976). This algorithm can be used for estimating short-time (one-hour to one-day) concentrations of relatively stable pollutants in urban areas emitted from point and area sources. The Air Force toxic chemical dispersion computer model AFTOX was developed for evaluating the extent of the hazard area resulting from the atmospheric dispersion of toxic vapors (Kunkel, 1991). This model is based on Gaussian formula, includes evaporation model and assumes formation of liquid pool at the ground after release of chemicals from the container. Schulman et al. (2000) suggested Plume Rise Model Enhancements (PRIME) based on Gaussian plume approach to describe plume rise and building downwash. PRIME considers the position of the stack relative to the building, streamline deflection near the building, and vertical wind speed shear and velocity deficit effects on plume rise. Grid-based approach is widely used to predict the impacts of emission controls on the atmospheric concentrations and deposition of pollutants such as ozone (O_3), fine particulate matter ($PM_{2.5}$), mercury (Hg) and other air pollutants. However, the grid-based approach necessarily averages emissions over the volume of the grid cell where the pollutants are released and cannot resolve