# Predicting Breathing Zone Concentrations of Aerosols Dispersed in a Time-Dependent Airflow Using Vortex Methods

Richmond-Bryant J A, Flynn M R
CB #7400, Department of Environmental Science and Engineering, University of North Carolina, Chapel Hill, NC, USA

## Introduction

When a person works facing a local exhaust ventilation (LEV) hood, it may be possible to obtain higher concentrations of aerosols in the breathing zone (BZ) than without the hood because recirculating eddies form downstream of the body. These eddies shed periodically in an alternating pattern called vortex shedding, which is thought to be a primary determinant of contaminant transport in and out of the breathing zone (1, 2, 3). Previous computational fluid dynamics (CFD) studies have explored the effect of time-dependent airflow on occupational exposure to gaseous contaminants (2, 3). However, none have employed CFD to assess occupational exposure to aerosols in a periodic air stream. In the present study, a two-dimensional Discrete Vortex Method (DVM) is used in conjunction with a Lagrangian particle-tracking algorithm to model this situation; particle number concentrations are then computed over a computational breathing zone.

## Methods

A two-dimensional DVM was utilized to model the time-dependent airflow field. The DVM treats the fluid as convecting elements of vorticity and employs random walks on each element to simulate turbulent diffusion (4, 2, 3). Specific details about implementation of the method can be found in the literature (4, 5, 6). A 1-m circular cylinder represented the worker; although this size exceeds that of a typical worker, this diameter was used to non-dimensionalize the Navier-Stokes equations of fluid motion. The Reynolds number was set at 10,000 to yield a fluid velocity of $2.46\text{x}10^{-1}$ m/s. A timestep of 0.13 s was employed, and the simulation was run for 1600 timesteps, or 208 s.

A Lagrangian inertial particle-tracking algorithm ran in conjunction with the DVM. During each fluid timestep, the equation of particle motion due to drag forces was integrated several times with an adaptive timestep Backwards Difference Formulae method. Particles having Stokes numbers (Stk) of $1.87\text{x}10^{-4}$, $4.63\text{x}10^{-3}$, $1.16\text{x}10^{-1}$, 1.00, and 5.00 were released at ten evenly-spaced points, from $x = -5.0\text{x}10^{-1}$ m to $x = 5.0\text{x}10^{-1}$ m, in separate simulations at $y = 7.5\text{x}10^{-1}$ m, $y = 1.0$ m, and $y = 1.5$ m downstream of the cylinder center, which was centered at (0, 0). Ten particles were released per timestep, beginning at the 100-th timestep (t = 13 s). Figure 1 illustrates the initial conditions of particle release. The particle injection source velocity was zero; thus, particles initially follow the fluid motion. Particle concentration was calculated following a method proposed in (8). A grid containing 2816 square elements was superimposed over the domain for the region x = –2.0 m to x = 2.0 m and y = –1.0 m to y = 10 m. Time-averaged concentrations were computed in a sub-domain from x = $-5.0\times10^{-1}$ m to x = $5.0\times10^{-1}$ m and y = 0 m to y = 1.0 m; this sub-domain is comparable to the BZ. The designated BZ is also shown in Figure 1.

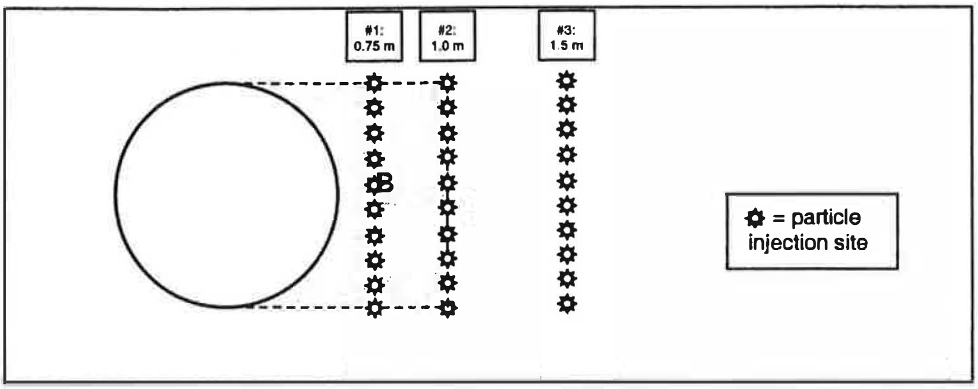


*Figure 1. Schematic of the initial particle injection locations and breathing zone.*

## Results and Discussion

Figure 2 demonstrates the effect of particle release position on the time-averaged concentration for Stk = $1.16\times10^{-1}$. Simulations with other particle sizes produced similar results. BZ concentrations for the downstream release site of $7.5\times10^{-1}$ m do not vary greatly with Stk. No consistent pattern between particle size and concentration level was observed. However, after this 208-s simulation, the time-averaged concentrations still have not reached steady-state values; hence, no conclusion can be drawn about the dependence of concentration on particle size. Accumulation of particles in the BZ is very noticeable for this set of runs because the site of particle injection lies within the BZ. Particles are injected into the domain faster than they can be effectively cleared from this region.

For the downstream release position of 1.0 m, BZ concentrations computed over the simulation time are lower than for the release position of $7.5\times10^{-1}$ m. For any Stk, some accumulation of particles in the BZ occurs, although it is at a slower rate than for the $7.5\times10^{-1}$ m injection site. It does appear that the Stk = $4.63\times10^{-3}$ particles yield slightly higher BZ concentrations than do particles of other sizes. Stk = $1.87\times10^{-4}$ and Stk = $1.16\times10^{-1}$ particles have the next highest concentrations, followed by Stk = 1.00 and Stk = 5.00. It is intuitive that larger particles will be cleared from the BZ at a faster rate and thus will yield lower concentrations. However, as is the case for the $7.5\times10^{-1}$ m injection site, the time-averaged number concentrations have not reached steady-state values, and therefore, any conclusions about the long-term concentration levels are premature.

In contrast with results from the other two injection positions, particle accumulation and overall concentration levels stabilize after some number of timesteps for the downstream release position of 1.5 m. A steady-state concentration level is then maintained for all Stk considered except Stk = $4.63\times10^{-3}$. At the release point of 1.5 m downstream of the cylinder, particles may either be reentrained into the recirculating bubble formed immediately downstream of the cylinder or they may be transported further downstream by the eddy which is being shed concurrently. This time-dependent behavior may explain why no clear relationship between BZ concentration and Stk can be garnered from these steady-state concentrations.

## Conclusions

The most significant conclusion from this work is that the rate of accumulation of particulate matter within the BZ is strongly dependent upon the distance between the contaminant source and the body. The results also suggest that particle concentration levels within the BZ may also rely heavily on source distance; however, it is impossible to draw any strict conclusions about this relationship until steady-state concentrations have been attained. Simulations with $7.5 \times 10^{-1}$ m and 1.0 m injection sites must be run for a longer period of time. No clear relationship between particle size and concentration level could be discerned from the results.

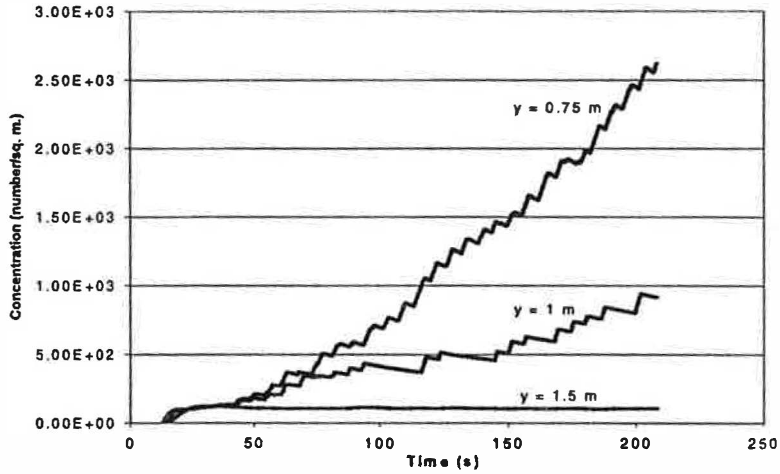


*Figure 2. Time-averaged particle number concentration for Stk = $1.16 \times 10^{-1}$.*

## References


1. Cantwell B, Coles, D. An Experimental Study of Entrainment and Transport in the Turbulent Near Wake of a Circular Cylinder. J. Fluid Mech 1983; 136: 321–374.
2. Flynn MR, Miller CT. Discrete Vortex Methods for the Simulation of Boundary Laye Separation Effects on Worker Exposure. Ann. Occup. Hyg, 1991; 35(1): 35–50.
3. Flynn MR, Chen MM, Kim T, Muthedath P. Computational Simulation of Work Exposure Using a Particle Trajectory Method. Ann. Occup. Hyg. 1995; 39(3): 277–289.
4. Chorin AJ. Numerical Study of Slightly Viscous Flow. J. Fluid Mech. 1973; 136: 321–374
5. Chorin AJ. Vortex Sheet Approximation of Boundary Layers. J. Comp. Phys. 1978; 2 428–442.
6. Ghoniem AF, Chorin AJ, Oppenheim AK. Numerical Modelling of Turbulent Flow in Combustion Tunnel. Phil. Trans. R. Soc. Lond. A. 1982; 304: 303–325.
7. White FM. Fluid Mechanics, 3rd Ed. New York: McGraw-Hill, Inc, 1994.
8. Lu QQ, Fontaine JR, Aubertin G. Particle Motion in Two-Dimensional Confined Turbul Flows. Aerosol Science and Technology 1992; 17: 169–185.