Asbestos fibre testing and monitoring

Aerodynamics of asbestos fibres

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Asbestos fiber can be assumed to be the discrete phase "particle" and its trajectory of dispersion is mathematically described using the Lagrangian equation. The Lagrangian scheme is most popular in engineering applications for the prediction of particle flows.

The Lagrangian discrete phase for individual particle trajectories can be expressed by integrating the force balance equations on the particle:

$$\frac{du_p}{dt} = F_D\left(u - u_p\right) + f_G + f_o \qquad (1)$$

where the subscript p refers to the particle phase, $F_D\left(u - u_p\right)$ denotes the drag force per unit particle mass (F_D is the coefficient related drag force). u and u_p denote the velocity of the air at the location of the particle and the velocity of the particle respectively. By the same token, ρ_g is the air density and ρ_p is the density of the particle, and hence the second term of equation (1), f_G, represents a gravitational setting. f_o shows all other forces acting on the unit mass of particles, such as Brownian force, f_B, and Saffman's lift force, f_S, or lift due to shear on a unit mass basis.

The drag force is basically derived from the Stokes' drag law, and F_D is defined as shown in Equation (2):

$$F_D = \frac{18\mu_g}{\rho_p d_a^2} \frac{C_D Re_p}{24} \qquad (2)$$

where μ_g is the air viscosity, d_a is the aerodynamic particle diameter (the particle volume equivalent diameter), and the Re_p is the particle Reynolds number, which is defined as:

$$Re_p \equiv \frac{\rho_p d_p \left| u_p - u_g \right|}{\mu_g} \tag{3}$$

C_D in equation (2) denotes drag coefficient and is given by following equation (4) in case of smooth spherical particles [1]:

$$C_D = \frac{24}{18} Re_p \left(18 + 0.367 Re_p^w\right), \text{ for } Re < 20 \tag{4}$$

$$w = 0.82 - 0.05\left(\log_{10} Re_p\right)$$

For non-spherical particles, such as asbestos fibres, mathematical expressions of the drag coefficient are known to be functions of Reynolds number (*Re*) and sphericity (or shape factor) ϕ. Most representative method might be elongated cylinder method [2].

$$C_D = \frac{24}{Re_p}\left(1 + t_1 Re_p^{t_2}\right) + \frac{t_3 Re_p}{t_4 + Re_p} \tag{5}$$

where

$$t_1 = \exp\left(2.3288 - 6.4581\phi + 2.4486\phi^2\right)$$

$$t_2 = 0.0964 + 0.5565\phi$$

$$t_3 = \exp\left(4.905 - 13.8944\phi + 18.4222\phi^2 - 10.2599\phi^3\right)$$

$$t_4 = \exp\left(1.4681 + 12.2584\phi - 20.7322\phi^2 + 15.8855\phi^3\right)$$

Sphericity (or shape factor) ϕ is defined as:

$$\phi = \frac{A_s}{A_p} \tag{6}$$

where, A_s denotes the surface area of a sphere having the same volume as the particle, and A_p is the actual surface area of the particle.

This elongated cylinder method is an empirical equation and has been confirmed to perform well for isometric particles with shape factors ϕ higher than 0.67, but fit poorer for shape factors lower than 0.23, or for cylindrical fibres with aspect ratios (length/diameter) up to around 15-20 [2, 3]. For example, it can be applied to fibers from 15 μm to 20 μm in length when the cross-sectional diameter is assumed to be 1 μm.

An alternative approach, clusters of spherical aggregate particles model which defines the fiber by spherical aggregate particles clustered into a cylindrical bar configuration has been reported and confirmed the reasonable prediction accuracy [4]. In this model, degree of circularity *c* is used for the drag correlation, and the empirically defined correlation for the drag coefficient is given as:

$$C_D = \frac{24}{Re_p}\frac{d_A}{d_n}\left[1+\frac{0.15}{\sqrt{c}}\left(\frac{d_A}{d_n}Re_p\right)^{0.687}\right]+\frac{0.42\left(d_A/d_n\right)}{\sqrt{c}\left[1+42500\left(\left(d_A/d_n\right)Re_p\right)^{-1.16}\right]} \tag{7}$$

Where, *c* is degree of circularity, d_n is the volume equivalent sphere diameter, d_A is surface equivalent sphere diameter, *V* is particle volume, A_{proj} is the projected area of the sphere, P_{proj} is the projected perimeter of the particle in its direction of motion.

$$c = \frac{\pi d_A}{P_{proj}}, \tag{8}$$

$$d_n = \sqrt[3]{6V/\pi} \tag{9}$$

$$d_A = \sqrt{4A_{proj}/\pi} \tag{10}$$

The second term of equation (1) represents a gravitational setting and expresses by equation (11).

$$f_G = g\left(1-\frac{\rho_g}{\rho_p}\right) \tag{11}$$

When the only external force acting on the particle is gravity, the equilibrium velocity is obtained by balancing the drag force received from the fluid with the gravity. This is called the terminal settling velocity and independent of its initial velocity. The equation of particle motion is described in equation (12).

$$\frac{4}{3}\pi a^3\left(\rho_p-\rho_g\right)g=\frac{1}{2}C_D\rho_g u^2\pi a^2 \tag{12}$$

Where, a is particle radius (=1/2 d_a). The terminal settling velocity u_s is expressed by equation (13).

$$u_s=\left[\frac{8}{3}\left(\frac{\rho_p}{\rho_g}-1\right)\frac{a}{C_D}g\right]^{1/2} \tag{13}$$

The modeling of Brownian motion for a small fiber particle is very complicated and is generally described by the Fokker-Planck equation associated with the Langevin equation, or can be modeled as independent zero-mean Gaussian white-noise process. For small and spherical particle, the Brownian force, f_B, can be expressed as equation (14).

$$f_B=\xi\sqrt{\frac{216\mu k_B T_g}{\pi d_p^5\rho_p^2 C_c\Delta t}} \tag{14}$$

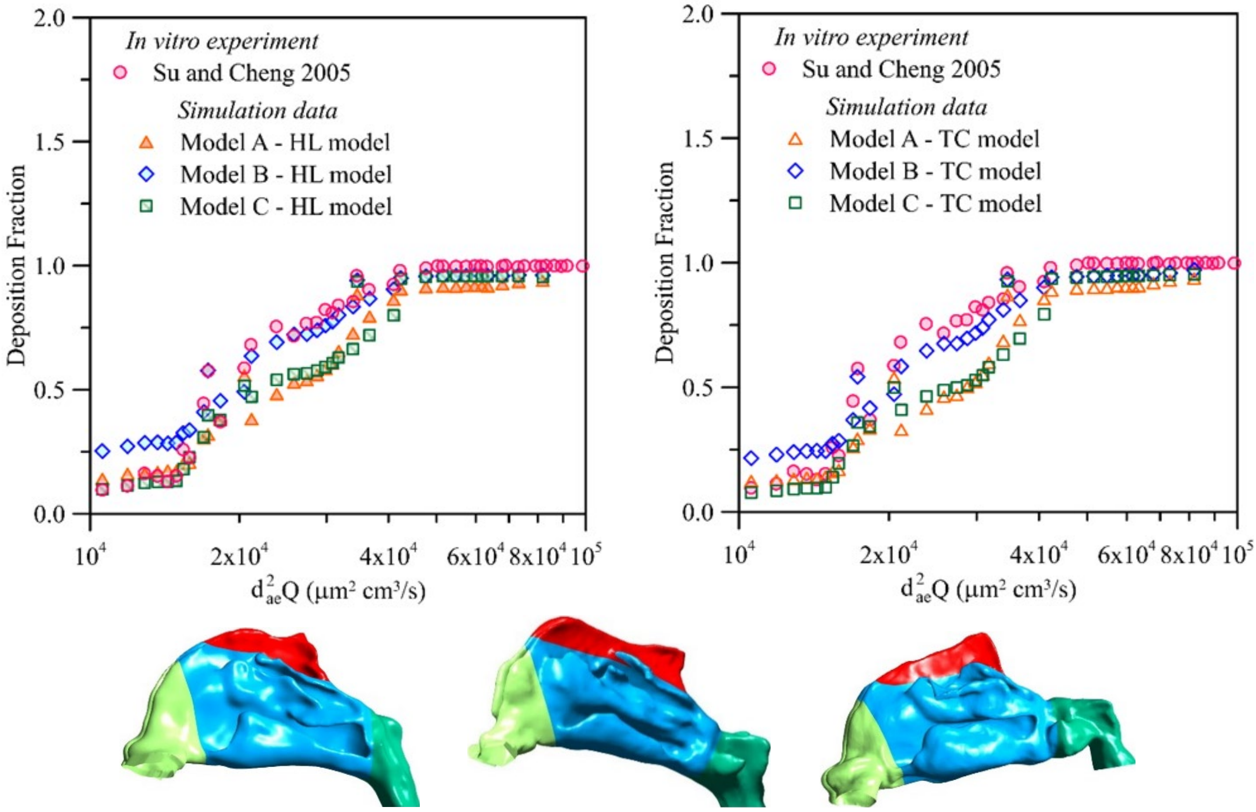
where ξ is a unit variance independent Gaussian random number, k_B is the Stefan–Boltzmann constant, T_g is the absolute fluid temperature, and Δt is the particle integration time step. The C_c is the Cunningham correction factor to Stokes' drag law. The appropriate and universal modeling for Brownian force for asbestos fibers is still an important research topic.

If the fluid flow is turbulent, the effect of turbulent fluctuations on particle transfer needs to be considered. To reproduce the particle turbulent dispersion due to turbulent fluctuations in the flow, a discrete random walk (DRW) model was adopted. Turbulent fluctuations in the flow field were represented by defining an instantaneous fluid velocity.

$$u'=\sigma\sqrt{\frac{2k}{3}} \tag{15}$$

where, u' represents instantaneous turbulent fluctuating component of fluid velocity, σ is a normally distributed random number and k is the turbulent kinetic energy.

The Lagrangian transport model for asbestos fibres shown in equations (1) to (15) has been applied to the numerical prediction of deposition distribution and deposition fraction in respiratory tract, and these modellings have been shown to be less accurate in the relatively low fluid velocity range. Further discussion and improvement of these models are needed.



Nasal cavity model A, Nasal cavity model B, Nasal cavity model C

Figure 1 Deposition fraction of Fibre particles in three nasal cavity models (Left: Haider and Levenspiel (HL) model, Right: Tran-Cong (TC) model)

Assuming inhalation exposure to asbestos fibers due to continuous breathing, it becomes important to understand the deposition phenomenon of asbestos fiber in the airway mucosa in addition to understanding the transport mechanism in the fluid. In case of the Lagrangian scheme, the fluid flow profile at the vicinity of the mucous surface in a respiratory tract has significant impact on a particle deposition and particle deposition flux is generally expressed as equation (16).

$$J = -v_d n \tag{16}$$

where, v_d denotes deposition velocity and n represents particle number concentration. This deposition velocity v_d corresponds to the mass transfer coefficient assuming that the mucosal surface concentration is zero, and it is assumed that the particles that reach the mucosal surface are completely and perfectly trapped by van der Waals forces and/or other forces. In the case of non-spherical asbestos particles, there has been insufficient discussion on appropriate wall boundary conditions, and future research is expected to be conducted.

References

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