Modeling of Bio-Aerosol Transport and Dispersion in a Ventilation Room

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The transport and dispersion of aerosol imbedded with influenza virus in a positively or negatively pressurized ventilation room is investigated by computational fluid dynamics (CFD) methods. Lagrangian stochastic (LS) walk model is used with several advantages of direct tracking of fluid particle trajectories, independence of the reference frame, and feasibility in conjunction with complicated flow environment. Influenza viruses are believed spread through the air via turbulent suspension and transport and infect others who walk in. The virus-containing bio-aerosols originate from the respiratory activities such as coughing and sneezing. The resulting germ-laden droplets may evaporate rapidly after they are released. Numerical simulation shows that it is justified to model these aerosols as passive scalars which neutrally follow the turbulent air flow, as a first approximation. Given the location of source (standing, sitting, or sleeping position), the semi-analytic LS model can predict the transport and dispersion of aerosols, and calculate the probability density function (PDF) or influence area of aerosols in the ventilation room. This model can also provide valuable information for ventilation control strategies with respiratory protection, such as enhanced air exchange, air filtration rate, and improved airflow patterns to reduce indoor airborne infection risk. Finally, the modeling results of this study can be extended to design and analyze virtual sampling tools for bio-aerosol particles.

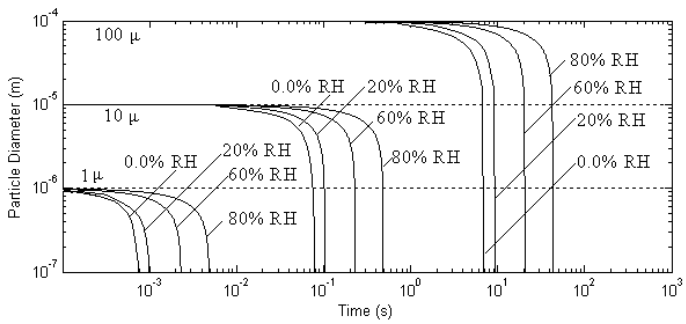
Introduction

The airborne transmission of disease is of great concern to the public health community because of the pandemic potential of newly-emerging diseases like avian influenza. Bio-aerosols have been referred as an important mode of transmission of influenza by many researchers (Tellier, 2006). Modeling of the dispersion of respiratory virus-laden aerosols in a ventilation room is an important approach to examine the safety and reliability of engineering control and implementation of infectious diseases. Numerical simulation can provide detailed three-dimensional information of infectious aerosols transmission at a given time which is hard to directly obtain from experimental observation or sampling. The spatial probability of distribution of aerosol production by simulation is effective for the risk evaluation of other airborne infections. A more general, yet practical, modeling of bio-aerosols in work places is required. The methodology for this study is to use computational fluid dynamics (CFD) methods to obtain instantaneous and mean flow field, and use Lagrangian stochastic (LS) walk model to analyze aerosol motion in air whose velocity is computed. One advantage of LS model is in obtaining the spatial probability of distribution of aerosol fairy easily. The approach is different from the Wells-Riley model that has been widely used to evaluate the risk factors for airborne infections (Chen et al. 2006; Fennelly et al., 2004; Nardell et al., 1991). The Wells-Riley model suffers from the negligence of effects of fluid flow (turbulence) on the spatial and temporal distribution of aerosols. Recently, a discrete-time Markov Chain model was used by Nicas and Sun (2006) to analyze infection risk, however, it did not consider effects of turbulence. While several works have been reported to simulate air flow and particle motion in ventilation environment by CFD (Sun et al., 2007; Kao and Yang, 2006; Li et al., 2004; Lu et al. 1996), most simulations have focused on airflow pattern, and neither of them directly analyzed turbulent stochastic of aerosol particles. To better understand aerosol transmission, the stochastic property of aerosols in turbulence should be considered. The objective of this study is to explore possible distribution of risk factors due to turbulence for influenza virus transport and dispersion in positively or negatively ventilated rooms. We restrict the simulation to neutrally buoyant particles in which case marked particles are released into a turbulent flow, and are dispersed by turbulence in the room. Instead of direct solving the particle equation either in an Eulerian or Lagrangian frame, we use LS model (a single-particle Markov-chain model) to simulate individual particle trajectories by assuming that its velocity can be represented by a Markov sequence. Given a prescribed flow field such as turbulent mean velocity, velocity variance and its gradient, the problem is posed to describe statistically the evolution of the aerosol field from a known initial state. A direct application of this study is that the numerical results can be extended to design and analyze virtual sampling tools for bio-aerosol particles. Other possible application is to provide recommendations for personal protective equipment by government health protection agency.

Numerical Modeling

In health-care environment or other work places, aerosol particles with an aerodynamic diameter (<10 μ m) remain suspended in air for a duration sufficient to permit dispersion through room air (Tellier, 2006). We simulated the temperature and size variation under evaporation for three sizes of aerosol particles using the standard single-droplet equation model (Crowe et al., 1998). Figure 1 shows that large size particles rapidly settle down close to point of emission (90%), only about 4~10% of aerosol particles disperse in room air (d< 10 μ m), and the time scale for process of evaporation of droplet from 5~10 μ m to 2 μ m is less than 0.1 s. Considering 1.0 m/s air velocity in the room, the maximum distance for particles with large size to settle down is about 0.1 m for 99% particles involved. The numerical model only investigates the transport and dispersion of aerosol particles within the size of 2 μ m after coughing. Therefore, it is reasonable to assume that the dispersion and transport of aerosol particles can be regarded as passive scalars (e.g., carbon dioxide). Thus, the dispersion of passive scalar (flu virus aerosols) by turbulent convection can be considered as an archetypal continuous stochastic process.

Figure 1. Evaporation of aerosol droplets with different sizes as a function of relative humidity (Droplet initial temperature is set as the same as 310.15°K and ambient air temperature of 293.15°K) and assuming a typical velocity profile of a coughing jet (Water droplets) in a room with uniform background flow field.

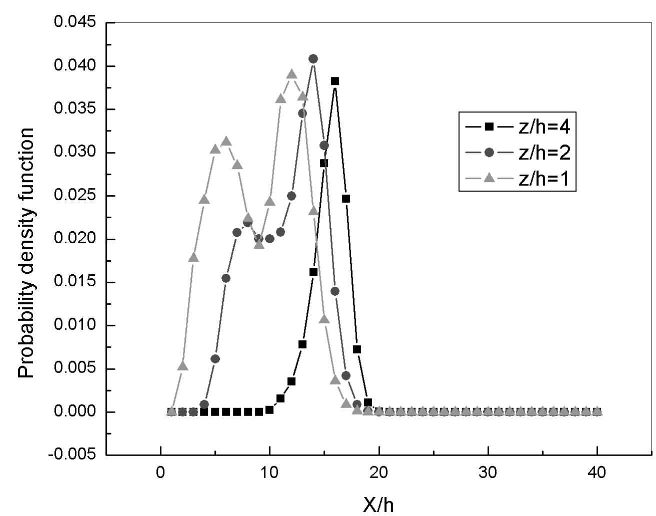


A Reynolds Averaged Navier Stokes (RANS) model was applied to find the turbulent mean flow field that is required by LS model. The continuous phase (air) solution is independent from the aerosol particle trajectories assuming that the particles do not affect the continuous phase. The turbulent diffusion and advection was computed in the vertical and horizontal directions by using a Lagrangian framework. The vertical displacement of aerosol is calculated from *dz=w•dt* (1) where w is the Lagrangian vertical velocity (fluctuation) and dt is differential time increment. Incremental change in vertical velocity were computed using the Langevin equation, an algorithm that is weighted by a deterministic forcing (which is a function of previous velocity of the particle) and a random forcing term, dw=a(z,t,w)*dt+b(z,t,w) dξ* (2). A similar process is used for horizontal directions. The coefficients a*(z,t,w)* and b*(z,t,w)* are non-linear functions of w, and are defined to account for inhomogeneous turbulence. The term *dξ* defines a Gaussian random forcing with a mean of zero and variance of *dt*. The terms a*(z,t,w)* and b*(z,t,w)* are derived from the Fokker-Planck equation for w (Durbin, 1983), and they are functions of Reynolds stresses, the standard deviation of velocity and , and the Lagrangian integral time scale . The variance of a random number is given by

$$\sigma_r^2 = \frac{1}{N-1}\left\{\sum_{i=1}^{N} r_i^2 - \frac{1}{N}\left(\sum_{i=1}^{N} r_i\right)^2\right\}$$

(3) In order to present the effects of entrainment and deposition of aerosol particles when in contact with the wall, a constant absorbing factor is used and the entrainment rate is taken proportional to √k, where k is the kinetic turbulent energy of particle. In indoor environment the height of the coughing source was selected as the length scale h. The length, width, and height of a room were 5m, 5m, and 2.5m, respectively. 10,000 particles were released from the coughing source at the same time, and the maximum flight time is 1000 s for statistical averaging. A general requirement is that the maximum flight time should be large enough for statistics. The time step used in the LS model was $0.1T_L$(0.1~1.0 s). The mean air velocity inside the room and its standard deviation were used as input parameter in the LS model. A numerical code has been developed based on the LS model. This code can directly output the concentration of aerosol and the probability density of its distribution. Figure 2 shows the probability density function (PDF) of aerosol distribution at different levels in a ventilation room. The risk of infection should be proportional to location of peak seen in each curve. There are three issues to be emphasized: First, the accuracy of PDF by LS model is determined by the mean air field and its fluctuation in the ventilation room. Different ventilation layout will result in different PDF profile. Numerical experiments showed that the transport of 70~80% aerosols is limited to 25 h in the horizontal direction if the ratio of room length to room height is larger than 10. Second, the PDF curve is obtained for a limited statistical period (1000 second). Third, different wall condition may result in slightly different PDF profile. Most notable is that we can examine the relationship between the aerosol concentration and the height of coughing source. The lower the height (z/h=1), the closer of the peak of PDF to the source. Under the same air flow field, the influence area of the case (z/h=1) is five times larger than the case of z/h=4. This seems reasonable because aerosols are expanding in vertical direction as the migration of aerosols along the horizontal direction proceeds. The maximum concentration will decrease due to the expansion in vertical direction. In a further work we plan to compare the calculated PDF with that obtained from samplers (Parsons et al., 2007, in this Options VI Proceedings).

Figure 2. Probability density function of aerosols along the horizontal direction at different height (1.0, 2.0, And 4.0, H is the height of the coughing source) by the Lagrangian Stochastic model by using a given mean air velocity in a ventilating room.



Conclusions

A Langrangian stochastic flight model was applied to examine the risk of infection in a typical ventilation room. This model is shown to be feasible for analyzing complicated indoor environment in which turbulence exhibit significant effect on the transport of aerosol particles. The numerical results showed that aerosol particles larger than 10 micron size rapidly deposit in a region of 0.1 to 0.25 m from the coughing source. The results were consistent with experimental data from other researchers. The deposition time scale for aerosol particles with large size (diameter d>10 μ m) is less than 0.1 s beyond that such particles evaporate and rapidly reduce in size. The calculated PDF profiles of aerosol particles in a typical ventilation room showed that peak of concentration moved away from the coughing source as aerosols propagate with air (the carrier phase). At the same ventilation condition aerosol particles significantly accumulated at the level of z/h=1 from the floor due to turbulent diffusion and indoor environment. This provides a direct estimation of influence area from a single source of influenza virus. To expand the application of Lagrangian stochastic walk model an accurate estimation of fluid flow field including turbulence is prerequisite in our future work.

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References
1. Chen SC, Chang CF, Liao CM. Predictive models of control strategies involved in containing indoor airborne infections, *Indoor Air*. 2006;16:469-481.
2. Crowe C, Sommerfeld M, Tsuji Y. Multiphase Flows with Droplets and Particles, CRC 1998; Press, 471p.
3. Durbin PA. 1983 Stochastic Differential Equations and Turbulent Dispersion, *NASA Reference Publication* 1103.
4. Fennelly KP, Davidow AL, Miller SL, Connell N, Ellner J. Airborne infection with backillus anthracis-from mills to mail, *Emerg Infect Dis.* 2004;10(6):996-1001.
5. Kao PH, Yang RJ. Virus diffusion in isolation rooms, *J Hosp Infect.* 2006;62:338-345.
6. Li Y, Huang X, Yu ITS, Wong TW, Qian H. Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong, *Indoor Air*. 2004;15:83-95.
7. Lu W, Howarth AT. Numerical analysis of indoor aerosol particle deposition and dispersion in two-zone ventilation system. *Building and Environ*. 1995;31(1):41-50.
8. Nardell EA, Keegan J, Cheney SA, Etkind SC. Airborne infection: Theoretical limits of protection achievable by building ventilation, *AM Rev Respir Dis.* 1991;144:302-306.
9. Nicas M, Sun G. An integrated model of infection risk in a health-care environment. *Risk Analysis.* 2006;26(4):1085-1096.
10. Sun W, Ji Jie, Li Y, Xie X. Dispersion and settling characteristics of evaporating droplets in ventilated room, *Building Environ.* 2007;42;1011-1017.
11. Tellier R. 2006: Review of aerosol transmission of Influenza A virus, *Emerging Infectious Diseases*, 12 (11), http://www.cdc.gov/ncidod/EID/vol12no11/06-0426.htm.

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