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Particle concentration dynamics in the ventilation duct after an artificial release: For countering potential bioterrorist attack

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HIGHLIGHTS

- Potential ways of harmful agents releasing in the ventilation duct are identified.
- Models of particle concentration dynamics for these releasing events are proposed.
- A series of wind tunnel experiments are conducted to validate the proposed models.
- The models provide the basis for assessing risk of harmful agents releasing events.
- Indoor airborne particle concentration models were derived.

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ABSTRACT

Ventilation duct serves as a potential target for bioterrorist attack. Understanding the dynamics of aerosolized harmful agents in the ventilation ducts provides the fundamentals for effective control and management, e.g., risk assessment. In this work, new models for predicting the concentration dynamics in the ventilation duct after a particle resuspension (representing the case that harmful agents are dosed when the ventilation is off and subsequently being turned on) or puff injection (representing the case that harmful agents are dosed when the ventilation is running) event were derived based on the mass balance model. The models were validated by a series of wind tunnel experiments. Indoor airborne particle concentration models were derived by incorporating the proposed ventilation duct models for resuspension and injection cases. The effects of resuspension and injection in the duct on indoor airborne particle concentration were examined by two hypothetical cases of *Bacillus anthracis* dosage using the derived models. For the same amount of BW agent dosage in the ventilation duct, the resuspension type release prolongs the exposure of harmful agents whereas the injection type release produces a higher peak concentration.

1. Introduction

The bioterrorist attack by the intentional release of biological weapons (BW) (e.g., viruses and bacteria) has drawn increasing attention worldwide since the anthrax letter attack of 2001 in the United States. The bioterrorist attack, once occurs, could produce great panic in the public due to its potential for causing massive civilian casualties. The economic impact of a bioterrorist attack could be as high as about $26.2 billion per 100,000 persons exposed to BW agents, suggesting the great economic burden to the society [1]. Hence, it is necessary to have effective measures to mitigate the attack once it happens. As one of important measures, the risk assessment of bioterrorist attack could provide useful information for defending against and mitigating the attack [2]. However, a robust risk assessment requires the knowledge about how BW agents are transmitted in the environment [3,4].

Recently, the United States government has warned that the ventilation systems of buildings are an ideal target for bioterrorism [5]. Actually, there was evidence showing that some terrorists were trained to inject harmful agents toward the air intake of a building [6]. Previous study [7] identified the role of ventilation duct in the dispersion of anthrax spores and indicated that even a small amount release of spores could be distributed throughout a high-rise building. However, there are still limited studies assessing the risk of bioterrorist attack through ventilation systems. The accurate risk assessment of ventilation-duct-based attack is further limited by the poor knowledge about the agent concentration variation in the duct. Hence, a model that can predict the dynamics of BW agent concentration in the ventilation duct after a deliberate release is of fundamental importance. Such model allows the prediction of indoor BW agent concentration and thus the exposure of residents to the agents.

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The bioterrorist attack through ventilation systems can be accomplished by two ways. Firstly, terrorists could deliberately place the BW agents onto the duct surface when the ventilation system is off (usually at night, therefore more covert). Some of these agents could be resuspended and transported into indoor environment once the ventilation is running, leading to mass contamination, as suggested by the existing studies [8–10]. Secondly, it is possible that the BW agents are directly injected into the duct when the ventilation is running. Some of these injected agents would be instantly transported into indoor environment along with the airflow, causing mass contamination.

Few studies have been conducted to investigate the particle concentration dynamics in the ventilation duct following a BW agent resuspension or injection event. Until recently, Zhou et al. [11] proposed a model for the particle concentration dynamics in the ventilation duct considering resuspension. However, their model was constructed based on the assumption that both the particle deposition and resuspension occur uniformly along the whole length of ventilation duct. This naturally makes their model inappropriate for cases where high concentration of particles are dosed in a small area in the duct and the initial resuspension occurs from that small area, usually in the case of bioterrorist attack. The governing equation in [11] was specifically organized to have a term accounting for the particle resuspension along the whole length. In the case of resuspension from a small area, this governing equation in [11] no longer holds and a simple substitution of the resuspension term in the governing equation is not physically reasonable. A different method is needed to solve the new governing equation corresponding to the case that initial resuspension occurs from a small area. Based on the mass balance approach, this work proposed new models for particle concentration dynamics in the ventilation duct following a resuspension or injection event. The proposed models were validated by a series of wind tunnel experiments. Indoor airborne particle concentration models were then derived by incorporating the proposed ventilation duct models for resuspension and injection cases. The effects of resuspension and injection in the duct on indoor airborne particle concentration are examined, respectively, by two hypothetical cases using the derived models.

2. Model derivation

2.1. Model for particle resuspension case

This part of model derivation concerns the case that particles (BW agents) are dosed into the ventilation duct when the ventilation system is off. The particles deposit (primary deposition) on a small area in the duct and are subsequently resuspended (primary resuspension) into the airflow stream when the ventilation is turned on. Only the initial (primary) resuspension is considered here, because (1) it plays the dominant role in affecting the airborne particle concentration over the secondary resuspension (subsequent resuspension of particles deposited on the duct surface downstream); (2) the amount of particles for secondary deposition is small and the amount for secondary resuspension would be even far smaller than that for secondary deposition, meaning that the net deposition could be well approximated by the secondary deposition; (3) the further consideration of the secondary resuspension will be a traversal problem that is prohibitive to solve. It is assumed

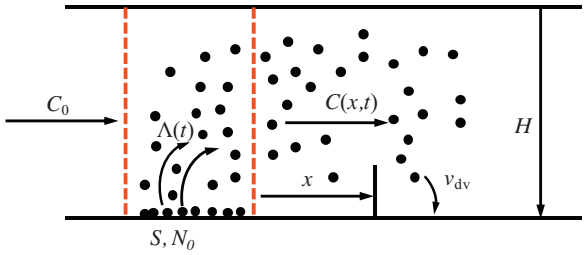

Fig. 1. A schematic of the particle resuspension in a duct.

that the length of the ventilation duct is much larger than the height and width of the duct. The transient particle concentration variation along the stream-wise direction$C(x,t)$ is concerned in the proposed model. The dimensions of the cross section of the wind tunnel's test section is 20 cm (W) × 20 cm (H) For such cross sectional dimension, the particle concentration variation in the bulk flow in the transverse direction of the cross-sectional plane is generally within a factor of 5 as shown previously [12,13]. Hence, particle concentration is assumed homogenous in the cross-section at any given point in x and t for simplifying the model development. Similar assumption was also adopted in the model of Zhou et al. [11]. As shown in Fig. 1, the particle resuspension occurs within the area of S (dose area of BW agents) where the particle surface number concentration is N_0. The particle concentration upstream the resuspension area is C_0, while the particle concentration downstream the resuspension area is $C(x,t)$. According to the conservation of mass, the mass balance model about $C(x,t)$ can be written as:

$$A\frac{\partial C(x,t)}{\partial t} + Q_s\frac{\partial C(x,t)}{\partial x} = -v_{dv}C(x,t)P \tag{1}$$

with the boundary condition of

$$C(x,t)|_{x=0} = C_0 + \frac{N_0 S\Lambda(t)}{Q_s} \tag{2}$$

and the initial condition of

$$C(x,t)|_{t=0} = C_{t0}, \tag{3}$$

where A is the cross sectional area of duct, Q_s is the volumetric flow rate, v_{dv} is the particle deposition velocity, P is the cross sectional perimeter of duct and Λ is the particle resuspension rate defined as the fraction of particles resuspended per unit time. The resuspension rate generally has a power law relationship versus time: $\Lambda(t) = r_1 t^{-r_2}$ [14–16]. After plugging the resuspension rate expression into Eq. (1), the solution of Eq. (1) is derived as (see Appendix A):

$$C(x,t) = \begin{cases} C_{t0}e^{-\frac{v_{dv}Pt}{A}} & \left(0 < t \le \frac{Ax}{Q_s}\right) \\ \frac{N_0 S r_1}{Q_s\left(t - Ax/Q_s\right)^{r_2}}e^{-\frac{v_{dv}Px}{Q_s}} + C_0 e^{-\frac{v_{dv}Px}{Q_s}} & \left(\frac{Ax}{Q_s} < t\right) \end{cases}. \tag{4}$$

In Eq. (4), Ax/Q_s defines the time when the location x will be affected by the resuspended particles. That is, when $0 < t \le Ax/Q_s$, the location x will have a concentration variation affected by the deposition only. Otherwise, the location x will have a concentration variation influenced by both particle resuspension and deposition.

Considering that the particle deposition velocities onto floor, wall and ceiling are different due to the effect of gravity, Eq. (4) is modified to

$$C(x,t) = \begin{cases} C_{t0}\ \exp(-(v_{dfv}P_f + v_{dwv}P_w + v_{dcv}P_c)t/A) & \left(0 < t \le \frac{Ax}{Q_s}\right) \\ \frac{N_0 S r_1}{Q_s\left(t - Ax/Q_s\right)^{r_2}}\exp(-(v_{dfv}P_f + v_{dwv}P_w + v_{dcv}P_c)x/Q_s) + C_0\exp(-(v_{dfv}P_f + v_{dwv}P_w + v_{dcv}P_c)x/Q_s) & \left(\frac{Ax}{Q_s} < t\right) \end{cases}, \tag{5}$$