Resuspension and Transport of Allergen-carrier Particles in Residential HVAC Systems

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ABSTRACT

HVAC systems play an important role in transporting allergen-carrier particles that trigger asthma episodes in residential indoor environments. Unfiltered particles deposited on interior duct surfaces resuspend and transport when disturbed under mechanical vibration and varying air flow conditions in the system. Experimental data is needed to characterize the behaviors of individual allergen-carrier particles in response to HVAC system disturbances and to inform modeling work that will lead to better design and performance guidance for builders seeking to improve indoor air quality in residential settings. In this study, a combination of experimental work in residential settings and in a more controlled laboratory resuspension chamber setup is conducted to characterize the resuspension of allergen-carrier particles deposited in residential HVAC ductwork and to obtain resuspension rate data for individual allergen-carrier particles in various HVAC system environments. The results of this research investigation are important to understanding the behavior of allergen sources in residential homes.

INTRODUCTION

Asthma is a life threatening disease that is affecting one in every ten residents in Pennsylvania. In particular, high rates of asthma hospitalization were shown for children and adults over 65 who tend to spend many hours at home (PDOH, 2012).

Despite attainment of general reductions in outdoor air pollutant levels, increases in asthma prevalence has led many researchers to focus on the home environment as a potential risk factor (Custovic et al., 1998).

Factors that are known to trigger asthma episodes include exposure to house dust and allergens (e.g., dust mite, cockroach, pet dander and fur dust, pollen). Allergens adhere to dust particles found in indoor air pathways (Gomes et al., 2007). Entrainment of dust in air supplied and recirculated in residential HVAC systems is affected by several aspects of the system design. Dust particles containing allergens deposit on interior duct surfaces, then resuspend and transport when disturbed under varying air flow conditions and mechanical vibrations in the system. Currently, ASHRAE 62.2 requires that HVAC system air filters meet a minimum efficiency reporting value (MERV) of 6 for residential applications (ASHRAE, 2010). At this MERV rating, the average particle size efficiency from 3 to 10 μm, is between 35 – 50%, which allows respirable (generally defined as particles less than 10 μm in size) unfiltered particles to remain a problem. Filter bypass, which is a common problem in HVAC systems, increases the dust load further. Hence, the potential for particles distributed through HVAC system ducting to affect indoor occupant exposure is significant.

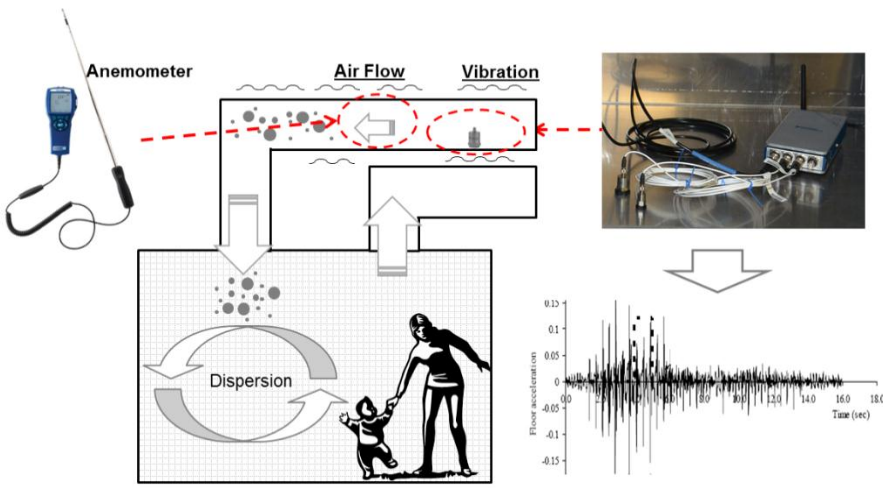
Although it is important to understand particle resuspension and transport behavior, experimental data is still limited. Previous studies (Wang et al., 2012) have attempted to analyze the lumped behavior of "average" dust particles resuspended in ducts. However, lumped behavior does not consider important aspects of individual allergen-carrier particles, whose resuspension behavior differs by particle type to various disturbances. Resuspension characteristics of individual allergen-carrier particles need to be investigated to gain insight into the impact of in-duct particles on occupant exposure and to develop best-practice mitigation approaches.

The objective of this study is to characterize resuspension and transport of allergen-carrier particles deposited in residential HVAC ductwork. Field measurements are carried out to establish the typical range of disturbances for residential HVAC duct settings. Subsequently, laboratory measurements are performed to measure resuspension rates of particles deposited on residential HVAC duct materials under the established disturbances. Measured resuspension data are used in the development of models to predict particle concentrations in the indoor environment, and to investigate the impact of in-duct particle resuspension and transport on occupant exposure, which is the broader goal of this work.

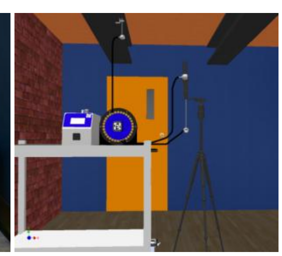
FIELD MEASUREMENT

Overview. Field measurement is designed to determine the particle disturbance factors in HVAC duct within actual residential settings. The measured disturbances are used for laboratory experiment and computational fluid dynamic simulation to quantify the particle resuspension rate and assess human exposure to indoor particle due to HVAC operation, respectively.

Measurement of mechanical vibration in the HVAC system. Mechanical vibrations in the HVAC ducting during start-up and steady-state operation of the packaged unit at various flows in the duct is measured using an array of accelerometers coupled to a wireless dynamic signal analyzer as shown in Figure 1a. Measurement locations are near the diffusers in the duct runs and at the air handler. Accelerometers are placed onto interior and /or exterior duct surfaces.



a.



b. **c.**

Figure 1. a. Schematic diagram of the field experiment at the MorningStar Solar Home; b. Particle sizing units that will be used to measure real time particle size distributions from 0.02 to 20 microns within the ductwork; c. Spatial profiling particle sizing set up.

Measurement of air flow, temperature and RH in the HVAC system. Air flow conditions in the HVAC duct are measured using multi-function anemometer probes and barometers at various set points for the packaged unit serving the duct runs.

Measurement of resuspended particles in the HVAC system. Resuspension of existing particles in the MorningStar Solar Home ductwork and the space served by the ductwork is measured within the ductwork and outside of the ductwork using particle counters shown in Figure 1b.

Injection of particles in the HVAC system. Minor quantities of monodisperse and natural particles are injected into the ductwork from the packaged unit inside the mechanical room as depicted schematically in Figure 2 with the diffusers covered to deposit particles on interior duct surfaces. Figure 3 shows photos of the MorningStar Home, measurement locations, and the packaged unit in the mechanical room. Subsequent measurements of particle resuspension are then made during normal operation of the mechanical system. Duct work is cleaned before and after this operation.

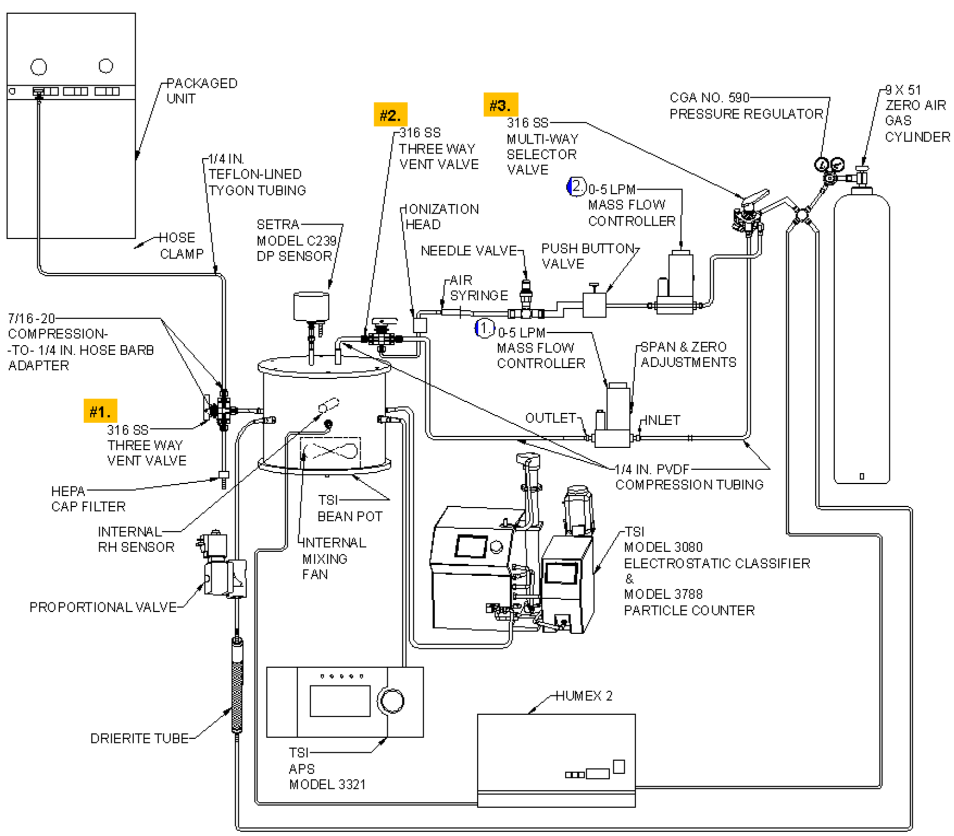


Figure 2. Schematic of apparatus layout for particulates injection into packaged unit

a.

b. c.

Figure 3. a. MorningStar Solar Home; b. Two of four measurement locations near duct diffusers; c. Packaged unit in mechanical room; red dots are approximate locations for ½ in. diameter traverse caps to be installed in the ductwork to enable velocity profiling and to fit particle injection line

LABORATORY RESUSPENSION EXPERIMENT

Overview. The laboratory resuspension experiment is designed to investigate the particle resuspension from various HVAC duct materials under the controlled HVAC disturbance forces. The measured actual HVAC disturbances such as mechanical vibration and air flow rates in the MorningStar Solar Home are replicated in the laboratory chamber experiment. The details of laboratory resuspension experiments are as follows.

Test Dusts and Flooring Samples. Quartz as a non-biological particle, and dust mite, dog fur dust and cat fur dust as biological particles are selected for this study. Quartz is one of the mineral aerosols which are commonly produced outdoors and enter through windows/cracks or are brought by occupants. Crushed Quartz #10 bt#4339 (Particle Technology Limited, UK) is used for the testing. For dust mite, Spent Mite Culture powder (Indoor Biotechnologies Inc., USA) is used. The dust mite samples are milled to produce fine mixed powder. The milled dusts are sieved to separate the particles. Dog fur dust and cat fur dust are prepared from respective pet animal fur collected from local pet grooming companies, which are then milled and separated using sieve. The grinding and sieving process is considered to prevent the dust particles from forming particle-to-particle agglomeration.

The particle size distribution of four test dusts is characterized using Wet and Dry Laser Diffraction (Mastersizer S, Malvern, UK) which has 64 bins between 0.05 and 900 μm. To confirm whether the test dusts represented typical indoor dust, the particle size distribution of test dusts is compared to that of Standard Reference Material (SRM 2583 Indoor Dust) distributed by NIST (National Institute of Standards and Technology). The NIST SRM 2583 is composed of dust collected from vacuum cleaner bags in dwelling space (US NIST 2010). For the experiment, typical metal duct and fibre-glass duct which are commonly used for residential duct systems are used as particle reservoirs. The dimension of each flooring sample is 90 mm x 90 mm.

Resuspension Chamber Experiment Setup To examine the resuspension behavior of test dusts affected by particle disturbances factors, which were measured in field tests, laboratory small-scale chamber experiments are performed in controlled temperature, relative humidity, background particle level of supply air and mechanical/aerodynamic disturbance conditions. The chamber system is originally constructed for the research of particle resuspension subjected to mechanical and aerodynamic disturbance (Gomes et al. 2007). Figure 4 shows the schematic diagram of resuspension chamber system. The system consists of a resuspension chamber, an air control system and a data acquisition (DAQ)/control system. The air control system consists of a temperature/humidity environmental chamber, a desiccant, a HEPA filter and pumps.

The resuspension chamber is made of stainless steel and has a size of 400 × 200 × 200 mm (L × W × H). The bottom center of the chamber has an area of 100 × 200 mm (L × W) where a test flooring sample is placed. As a part of the chamber, an actuator-induced mechanical shaker (F4, Wilcoxon, USA) and six aerodynamic air-jet nozzles made of copper are embedded beneath the chamber to stimulate the flooring sample with the vibration and air swirl caused by occupant walking. The controlled air supplied from the air control system is passed into the resuspension chamber. An inlet porous panel (1100S-0039-02-A, Mott Corp., USA) is installed at the longitudinal square cross section of the entrance of the chamber to ensure uniform distribution of the air. The laminar air flow sweeps the chamber carrying resuspended particles into the sampling line attached to the exhaust port. The exhaust flow is collected through an optical particle counter. The pressure inside of the chamber is measured by a pressure gauge (2020S AKPT, Orange Research, USA) to ensure the chamber was pressurized relative to the laboratory.

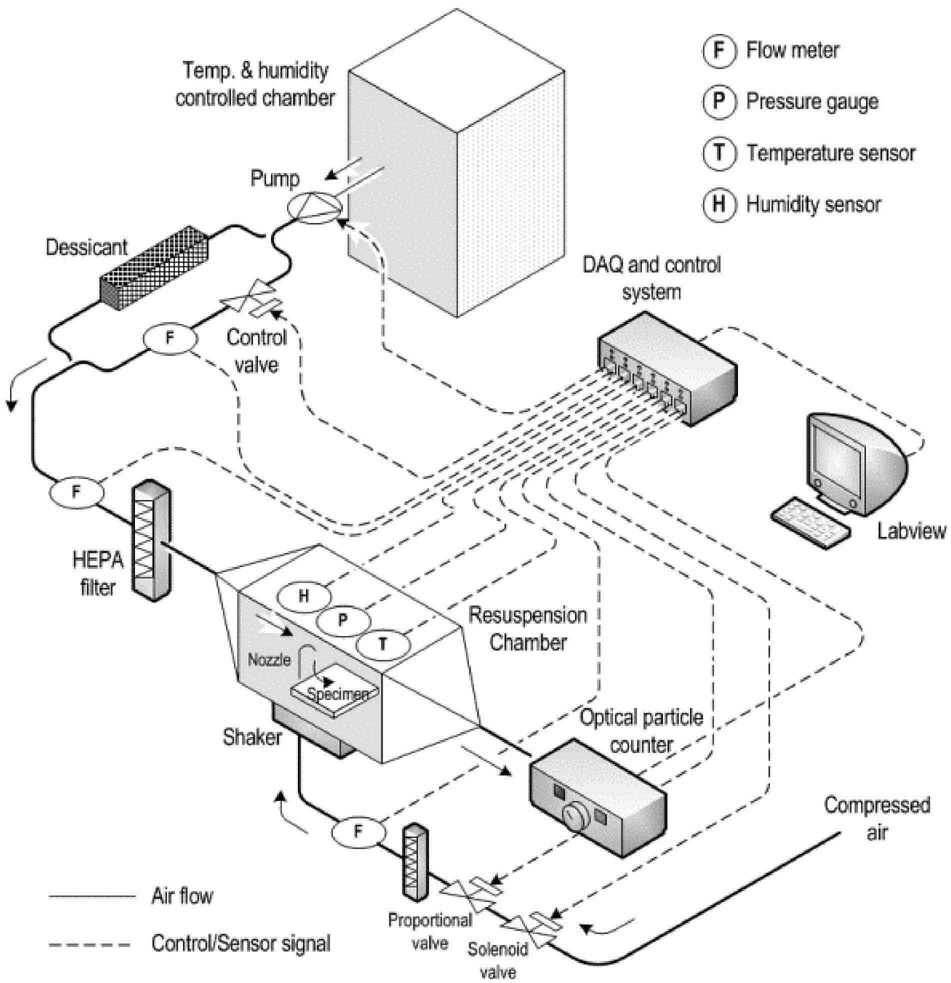


Figure 4. Schematic diagram of resuspension chamber system

The humidity and temperature of the supply air is controlled using a temperature/humidity environmental chamber (SM-8-3800, Thermotron, USA). The environmental chamber provides temperature range from -70 ℃ to 180 ℃ and humidity range from 35% to 97% at 21 ℃. The air from the environmental chamber is mixed with the air from the desiccant cartridge to meet desired humidity conditions using a proportional mixing valve. The temperature/humidity controlled supply air is filtered (HEPA CAP36, Whatman, UK) and pumped (1532-101-6288X, GAST, USA) to the resuspension chamber. The temperature and relative humidity within the resuspension chamber is monitored by a temperature/humidity sensor (HX15-W, OMEGA, USA).

The experiments are controlled and the data from sensors and optical particle counter were collected in a data acquisition (DAQ)/control system. For a high degree of automatic control and data acquisition, LabView (version 8.20, National Instrument, USA) is used communicating with a DAQ board (PCI 6259, National Instrument, USA).

Seeding and Measuring Procedures. To uniformly seed the test dusts on flooring samples for resuspension experiments, a particle disperser chamber is used. The chamber is made up of glass and stainless steel plates with dimensions of 760 × 760 × 420 mm (L × W × H), which is sealed and air tight. Total of nineteen flooring samples are laid out in five rows with five samples in each row except in the middle, where a particle injection nozzle is located. Each test dusts are injected in the amount 3 g m^{-2} by a compressed air line from a scale syringe to a cone, which is attached at the end of the particle injection nozzle. An air-jet is simultaneously injected from another nozzle hung from the top of the chamber to impact the cone. At the same time, four miniature fans placed in each of the four corners of the chamber are activated to ensure uniform dispersion of the dusts.

After the seeding process, the flooring samples are placed in a sample conditioning chamber with protective lids for at least 24 hours before each resuspension experiment to give sufficient time to reach the desired relative humidity equilibrium. The sample conditioning chamber is a plastic storage container, which enabled the samples to be controlled at desired relative humidity conditions. The conditioned flooring sample is placed in the resuspension chamber, and then the supply air is introduced at the flow rate of 0.0259 m^3 min^{-1}. Simultaneously, disturbance signal is activated and the particle concentration is measured at the exhaust port of the resuspension chamber. Sixteen-second disturbance signal ran for four minutes. Air samples from the chamber are measured using an optical particle counter (Spectro .3, Climet Instruments, USA) with a sampling rate of 7.9×10^{-3} m^3 min^{-1}. The optical particle counter has 16 bins between 0.3 to 10 μm. The particle concentration is measured every second per unit of air volume during 4-min testing period. During the resuspension experiments, the mechanical vibration and air flow patterns measured in MorningStar Solar home is replicate in the resuspension chamber by using the accelerometer and air nozzles located in the resuspension chamber.

Before each test, the particle disperser chamber and resuspension chamber are thoroughly cleaned. To check the cleanliness of the resuspension chamber, the background sample of the particle concentration is taken prior to each test. The LabView code in the DAQ system enables monitoring the real-time background data from the optical particle counter until the number reached a threshold value of 5 particles m^{-3}.

Estimation of resuspension rate. Resuspension rate (RR) is calculated as the fraction of a surface species removed in unit time as shown in Equations (1) and (2).

$$RR_d = \frac{G_d}{C_{d,surface}}, \tag{1}$$

$$G_d = \frac{\int_t Q_{sampling} \cdot C_{d,air} dt}{A_{surface} \cdot \frac{1}{60} \cdot \int_t dt}, \tag{2}$$

where RR_d is the resuspension rate for particle size d, G_d is the surface removal rate for particle size d, $C_{d,surface}$ is the surface dust concentration for particle size d, $Q_{sampling}$ is the sampling air volume flow rate, $C_{d,\ air}$ is the air dust concentration for particle size d, $A_{surface}$ is the surface area. The mean value of the 2-min data is used as a representative resuspension rate for each particle size of test dusts.

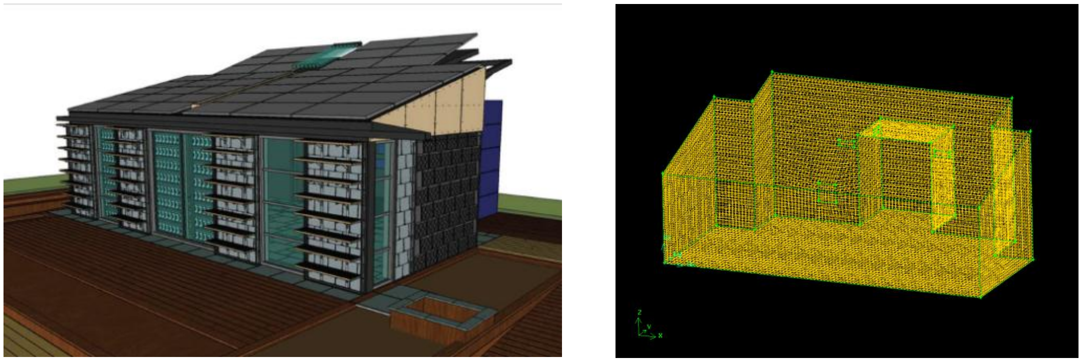
CFD (COMPUTATIONAL FLUID DYNAMICS) SIMULATION

Overview. Indoor airflow and particle dispersion in a Morning Star Solar Home is simulated by CFD modeling. Resuspension data previously measured in the laboratory resuspension experiment are used in the development of models to predict particle concentrations in the indoor environment, and to investigate the impact of in-duct particle resuspension and transport on occupant exposure.

Indoor Airflow and Particle Transport Analysis. The indoor airflow is modeled by the renormalization group (RNG) *k-ε* turbulence model. The RNG *k-ε* turbulence model is suggested to be suitable for indoor airflow simulation. The particle dispersion is modeled by a Lagrangian discrete random walk (DRW) model. The Lagrangian method solves the momentum equation based on Newton's law to calculate the trajectory of each particle. This study uses Fluent 6.0 with GAMBIT as a pre-processor for the simulation.

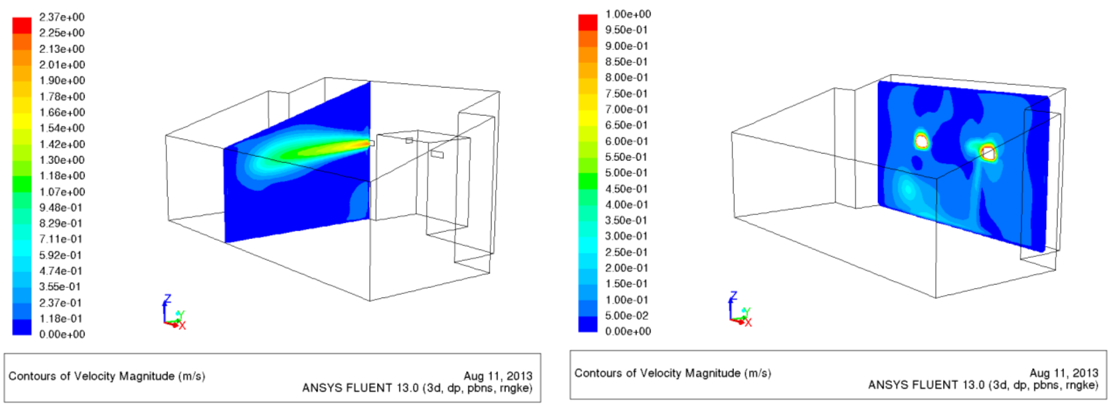
$$\frac{du_p}{dt} = F_D(\overrightarrow{u_a} - \overrightarrow{u_p}) + \frac{g(\rho_p - \rho_a)}{\rho_p} + \overrightarrow{F_a} \tag{3}$$

where u_p is velocity vector of the particle; u_a is the velocity vector of the air; $F_D(u_a - u_p)$ is the drag force per unit particle mass; ρ_p is the particle density; ρ_a are the air density; g is the gravitational acceleration vector, and F_a is the additional forces.



a. **b.**

Figure 5. a. 3-dimensional modeling of MorningStar Solar Home; b. CFD mesh generation



a. **b.**

Figure 6. a. Velocity magnitude contour plot on the YZ cross-section plane near supply register; b. Velocity magnitude contour plot on the XZ cross-section plane near supply register and return grill

Figure 5 shows the 3-dimensional modeling of MorningStar Solar Home and the result of CFD mesh generation. Figure 6 shows the velocity magnitude contour plot on the YZ cross-section plane near supply register and the velocity magnitude contour plot on the XZ cross-section plane near supply register and return grill.

Particle Concentration Analysis. PSI-C (particle source in cell) method is used to calculate the particle concentration in the modeled space [Bin paper 9].

$$C_j = \frac{\dot{M}\sum_{i=1}^{m} dt_{(i,j)}}{V_j} \qquad (4)$$

where C_j is the mean particle concentration in a cell, V_j is the volume of a computational cell for particles, dt is the particle residence time, and subscript i and j represent the ith trajectory and the jth cell, respectively. $\dot{M}$ is the flow rate of each trajectory.

Validation of CFD model. To validate the CFD model described above, the experimental data from the previous research is used. The experiment was carried out for the particle of which diameter of 10 μm in the space of 0.8 m× 0.4 m × 0.4 m (Length × Width × Height). The CFD model for validation was identically set to have the same location of openings, diffuser location and air velocity as the experimental case.

CONCLUSION

The research is currently ongoing, partially funded by PHRC (Pennsylvania Housing Research Center). The experimental setup required for the field and laboratory experiments has been completed as described in this paper. Also, CFD model to assess human exposure to indoor particle has been done. The study will measure the disturbances of particle resuspension in MorningStar Solar Home and subsequently conduct the resuspension chamber experiment to rigorously quantify the particle resuspension rates suggested in this paper. Finally, the particle resuspension rates for the various indoor particles and duct materials will be used for CFD simulation to assess human exposure to indoor particles. It is expected that the research can contribute to assessing the health risk of occupants due to exposure to indoor particulate, which may be induced by HVAC duct.

REFERENCES

The Pennsylvania Department of Health. (2012). “Pennsylvania asthma burden report.”

Custovic, A., Smith, A., and Woodcock, A. (1998). “Indoor allergens are a primary cause of asthma.” *European Respiratory Review*, 8(53), 155-158.

Gomes, C., Freihaut, J.D., and Bahnfleth, W. (2007). “Resuspension of Allergen-Containing Particles under Mechanical and Aerodynamic Disturbances from Human Walking.” *Atmos. Environ.*, 41, 5257-5270.

ASHRAE. (2010). “Ventilation and acceptable indoor air quality in low-rise residential buildings” Standard 62.2, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta.

Wang, S., Zhao, B., Zhou, B., Tan, Z. (2012). “An experimental study on short-time particle resuspension from inner surfaces of straight ventilation ducts” *Build. Environ.*, 53, 119-127.

Zhao, B., Yang, C., Yang, X., and Liu, S. (2008). "Particle dispersion and deposition in ventilated rooms: Testing and evaluation of different Eulerian and Lagrangian models" *Build. Environ.*, 43, 388-397.

Zhang, Z., Chen, Q. (2006). "Experimental measurements and numerical simulation of fine particle transport and distribution in ventilated rooms" *Atmos. Environ.*, 40, 3396–3408.