7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Fate of particles released by a puff–dispersion with different air distributions

Shichao Liu[1,*], Atila Novoselac[2]

[1]Department of Civil and Environmental Engineering, Worcester Polytechnic Institute, USA
[2]Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, TX, USA

Corresponding email: sliu8@wpi.edu

ABSTRACT
Well-mixed assumption normally has flaws in the space with continuous-releasing particle sources. For transient point or puff sources, however, particle concentration might vary differently among locations during emission periods and afterwards. This study measures whether and how rapidly ventilation systems can distribute particles emitted from puff-like sources in an indoor space. The impact of ventilation pattern (over-head mixing ventilation and displacement ventilation), particle size (0.77, 2.5 and 7 µm) and source location are also examined. The results show that particles with sizes of 0.77 µm and 2.5 µm can be distributed uniformly by both mixing ventilation and displace ventilation shortly (within a few minutes) after particle injection is terminated, regardless of particle source locations with the absence of obstructed airflow. This paper validates the well-mixed assumption when assessing long-term human exposure to puff-generated particles in the indoor environment. With regard to puff sources, the spatial concentration enhancement in human microenvironment/breathing zone might not be as significant as continuous-releasing particle sources.

KEYWORDS
well-mixed assumption, puff, mixing time, displacement ventilation (DV), mixing ventilation (MV)

INTRODUCTION
The assessment of human exposure to indoor particles relies on the information of particle concentration and spatial distribution. The well-mixed assumption is a convenient approximation in the human exposure analysis (Mosley et al., 2001). In many situations, however, particle size and source location affect indoor fate and lead to spatial variability of particle concentration (Bouilly et al., 2005). Rim and Novoselac (2009) found that thermal plume of a sedentary manikin caused up to four times higher concentration in the breathing zone than room concentration with stratified airflow patterns in the room. Air distribution patterns or ventilation systems also cause inhomogeneity of spatial distribution (Zhao and Wu, 2009). These findings on the inadequacy of the well-mixed assumption presume that indoor particles are released from stationary and continuous injecting sources.

Indoor particle sources are often transient, mobile, and in the form of puff-dispersion. Intermittent human activities such as folding clothing, walking around and sitting on upholstered furniture resuspend substantial particles smaller than 5 µm (Ferro et al., 2004). During particle releasing, spatial concentration is greater near the source than other regions. The non-uniformity decays after the particle releasing finishes. The well-mixed condition can be achieved when the standard deviation of the concentration at all locations to be within 10% of the spatial average (Gadgil et al., 2003).

Since human activities release substantial indoor particles near a human body, this study investigates the fate of particles (0.77, 2.5 and 7 μm) released from a puff-like source in the feet region of an occupant, which simulates particle resuspended from the floor or shed from clothing (pants). Injecting a blast puff of particles in the supply air, we also examine the influence of source location on the mixing time of indoor particles.

The primary objective of this study is to re-visit the well-mixed assumption for indoor particles released from puff-like sources. In addition, this study aims to investigate particle mixing time when considering different indoor ventilation systems (overhead mixing and displacement ventilation), particle sizes and source locations.

METHODS

Test chamber and setups

The test chamber for all particle experiments consisted of a precisely controlled HVAC system and a water-heating wall. The chamber had a geometry of 6 m × 4.5 m × 2.7 m. It is able to create displacement ventilation and mixing ventilation by using different air diffusers (Figure 1). Both overhead mixing ventilation (MV) and displacement ventilation (DV) provided an air change rate per hour (ACH) of 3.2 hr^{-1} that represented a typical office environment. The supply air temperature and turbulence intensities were approximately 17.4 °C and 5%, respectively, which were measured by a hot sphere anemometer (HT-400, SENSOR) with a sampling frequency of 0.5 Hz. This study considered a relatively low-occupation-density office that consisted of two thermal dummies (90W each), two table-boxes (0 W) and one heated wall (320W) representing warm windows or façade in the summer time (Figure 1). An embedded HEPA (high-efficiency particulate arrestment) filter in the HVAC system enabled background particle concentration without indoor sources three order of magnitudes lower than that with such sources.

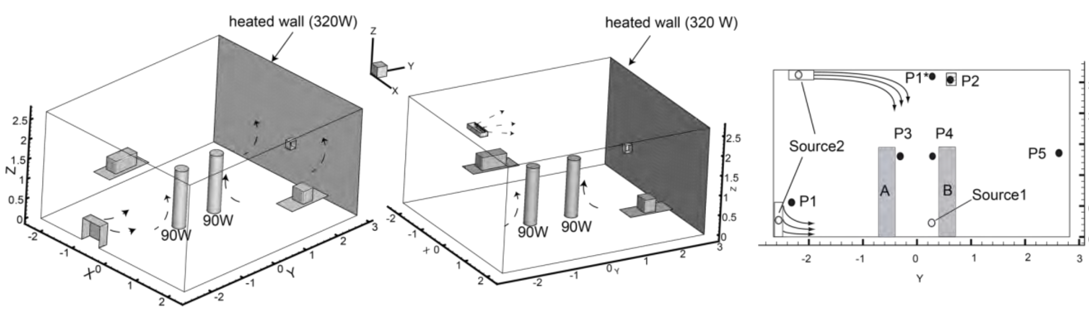

Figure 1. Schematic of experimental setups. Left) displacement ventilation, Middle) mixing ventilation, Right) particle sampling positions.

Particle seeding and measurements

Outdoor particles and indoor human activities contribute to indoor particles. Particle sources described in Figure 1 represents resuspended particles (Source 1) from the floor or shed particles from clothing because of human activities and unfiltered outdoor particles entering indoors via supply air (Source 2). We tracked the fates of particles with three different sizes, 0.77, 2.5 and 7 μm considering particle and airflow dynamics (Liu and Novoselac, 2014).

For both DV and MV, particles were released close to body proximity (Source1) (0.02 m from a dummy and 0.3 m above the floor) or in the duct before diffusers (Source 2). Coarse particles (7 μm) were released only in the duct due to the strong flow disturbance of the generator. The generation period was 100 seconds for 0.77 and 2.5 μm particles, while 30 seconds for 7 μm particles. We measured particle time-serial concentration at five locations (Figure 1) for 1200 seconds across the chamber using Optical Particle Counters (Aerotraks 9306, TSI, Inc). All experiments were repeated three times and measurements uncertainty is represented by standard deviation among the three repeats in this study.

In order to facilitate concentration comparison at the different sampling locations, this study normalized particle concentration by a reference value. For 0.77 and 2.5 μm particles, we used the average concentration over the entire sampling period (1200 seconds) at the chamber exhaust (P2 in Figure 1) as the reference (C_{ref}). Nevertheless, particle deposition loss becomes significant for 7 μm particles. As such, we normalized particle concentration for 7 μm based on the instantaneous average concentration over the five sampling locations, C^{*}_{ref}. This study focuses on the instantaneous comparison of particle concentration at different locations. The reference value does not affect the comparison of spatial concentration.

RESULTS

Mixing ventilation

Supply air diffusers for MV typically create high-momentum jets that entrain air and particles from surroundings and blend them inside the whole room. The concentration of submicron particles that transport similarly to gaseous pollutants tends to be uniformly distributed in the room with MV. Figure 2 shows the measured time-serial concentration of particles (0.77, 2.5 and 7 μm) released from two sources. When the particle source (Source1) resides in the vicinity of thermal dummy B, convective boundary flow of the thermal dummy spreads particles during the injection period. In Figure 2, the concentration right above the particle source (P4) is approximately two orders of magnitude higher than at other locations for 0.77 and 2.5 μm particles during injection. Nevertheless, this difference disappears a few minutes after particle injection finishes, rendering all concentration curves collapsing onto one. When particles were released into supply duct (Source 2), on the other hand, the concentrations at five locations show a very similar trend for both 0.77 and 2.5μm particles. With regard to 7 μm particles, the gravitational force becomes competing with drag force, leading to increased deposition loss and decayed concentration with height.

The results for MV indicate that particle source locations only affect $PM_{2.5}$ transport during the injection period and the relatively short period (**2 min**) afterward. The well-mixed assumption concentration is valid for transient puff-like particle sources in the typical office environments when considering particle distribution and human exposure for a long term. However, the assumption does not hold for coarse (e.g. 7μm) particles.

Displacement ventilation

Particles take a longer time to transport across the chamber with DV than MV, because DV supplies air at the floor level at a low air speed. In Figure 2, particles (0.77 and 2.5 μm) emitted at the feet region (Source 1) of the thermal dummy B are transported by the plume to the breathing zone of thermal dummy A (P4) where concentration is one order of magnitude greater than that at room exhaust during particle injection. Compared to the concentration at P4 for MV, DV reduces considerably the peak concentration in the breathing zone. This reduction is attributed to the enhanced airflow disturbance on Source 1 (feet region) when supply air is provided at the floor level.

When outdoor or room-recirculated particles enter the room with DV via supply air diffusers (Source 2), particles transport along the floor and then upwards with thermal plumes when encountering heat sources. Figure 2 shows that particle concentration in the locations close to

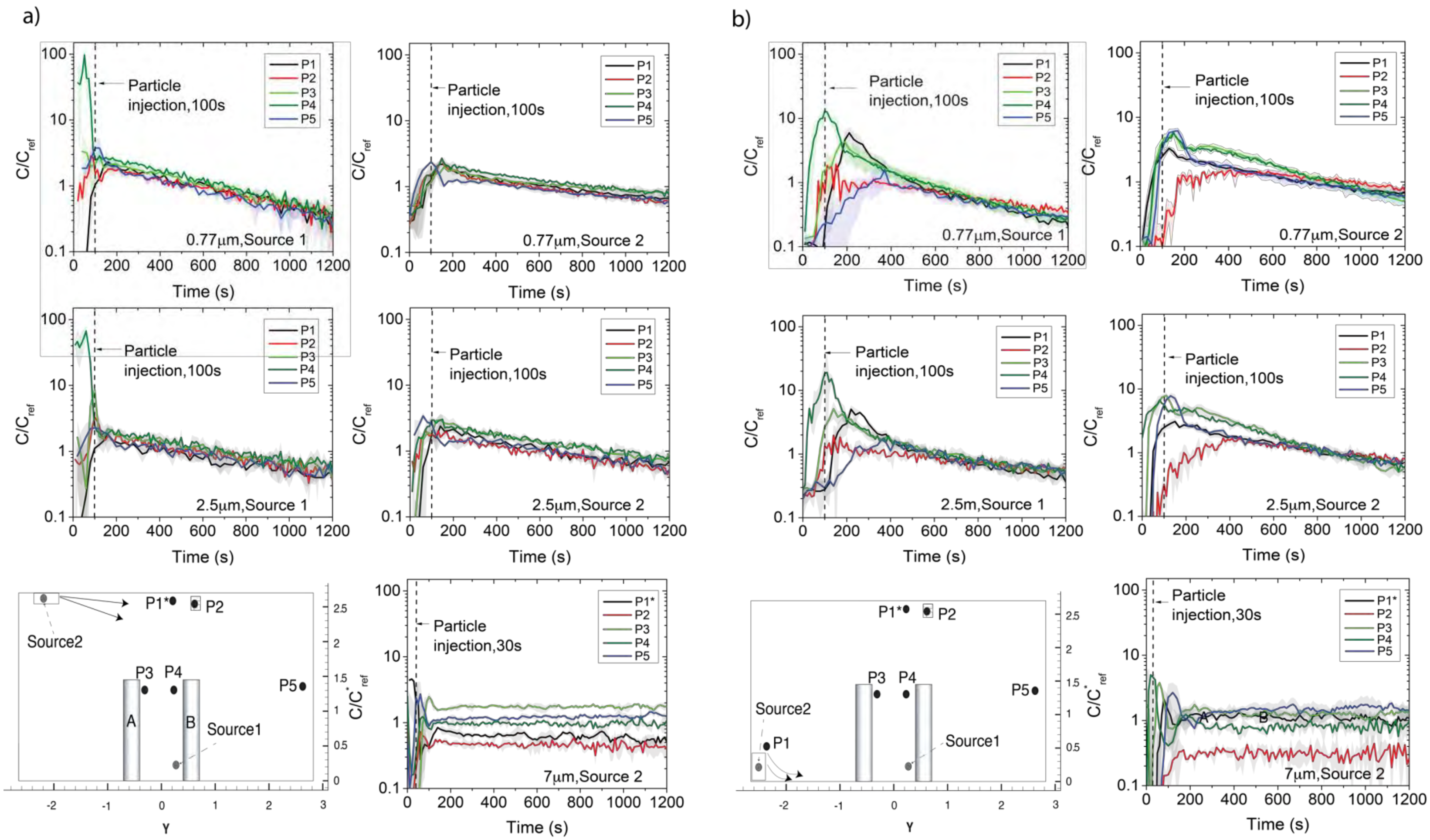

Figure 2. The variation of particle concentration in the room. a) mixing ventilation, b) displace ventilation (cooling condition, ACH=3.2 hr^{-1}, exhaust: P2; curve shades represent uncertainty). Note: P2 is the exhaust on a chamber wall, and all other locations are at the central plane of the room

thermal plume such as P3, P4, and P5 are higher than other measured locations during and in the short period after particle injection finishes.

Unlike creating thermal stratification, DV fails to generate stratified concentration for 0.77 and 2.5 μm particles. It is observed in Figure 2 that particle concentrations for the two sizes at all the measured locations decay to the same level in 10 min after particle injection ends. The results suggest that puff-like sources transport $PM_{2.5}$ uniformly across a typical office environment shortly after the particle-releasing period, even for thermally stratified systems. Source locations have little effect on the well-mixed assumption for $PM_{2.5}$.

We also measured particle concentration at $P1^*$ that is near the room ceiling and right above the breathing zone (P4) of thermal dummy B. Figure 2 shows that particle (7μm) concentration at $P1^*$ is at the same magnitude of that at breathing zones (P3 and P4). The observation implies human thermal plume is able to transport coarse particles (7 μm) from the floor up to the ceiling level. Again, coarse particles (7 μm) settle down easily in the indoor environment, and well-mixed assumption is unjustified.

DISCUSSIONS

Airflow in a typical office with MV distributes uniformly $PM_{2.5}$ that constitutes most indoor particles shortly (2 min) after particle injection period. As a stratified system, DV spreads particles generated by puff-like sources and is able to homogenize particle distribution in 10 min after particle generation finishes. The location of particle sources has insignificant influence on the mixing time. However, such phenomena are not observed in the similar indoor environments for continuously releasing sources. For instance, when particles are continuously released in the vicinity of a human manikin, exposure increases significantly compared to other particle sources (Rim and Novoselac, 2009, 2010; Salmanzadeh et al., 2012). These findings assuming continuous particle sources propose a scrutinized investigation in the spatial difference of particle concentration for further exposure analysis. In a real office environment, however, intermittent and short-term puff-like sources, such as walking, body shedding and printing, are much more common than stationary continuous particle sources. The findings from this study imply that $PM_{2.5}$ is likely to be uniformly distributed if considering long-term exposure. The findings for $PM_{2.5}$ also justify the well-mixed assumption shortly after particle injection ends, regardless of particle location.

In addition, spatial variability of particle concentration occurs during particle injection and only a few minutes afterwards. Such short period makes source-localization that applies inverse tracking techniques more challenging to identify puff-like sources of $PM_{2.5}$ or gaseous pollutants (Zhang et al., 2012).

We measured particle transport in a test chamber where interior surfaces might be different in surface roughness and area from offices in reality (Thatcher et al., 2002). In addition, the study considered no furnishing obstructing airflow around particle sources. The findings from this study might be generalized to other short-term puff-like particles sources, such as coughing and sneezing rather than intermittent repeatable sources including breathing and chatting. Other factors such as air change rate per hour, heating source intensity and the number of particle sources might affect particle fate. These factors should be investigated in future.

CONCLUSIONS

We investigated the fate of particles generated by transient puff-like sources in a test chamber that simulated a typical office environment. We also examined how ventilation pattern, particle size and source location affected particle transport across the room.

This study concludes that both MV and DV can distribute uniformly $PM_{2.5}$ released by a puff-like source in the entire room shortly after particle generation finishes. In specific, particle concentration varies insignificantly among different locations in 2 min and 10 min after particle source terminated for MV and DV, respectively. However, gravitational settling generates concentration stratification for coarse particles (7 μm) in the room.

The study justifies the well-mixed assumption for $PM_{2.5}$ related to puff-like sources in the indoor environment if considering long-term exposure. In such conditions, long-term human exposure in the microenvironment might not be significantly different from other room space.

REFERENCES

Bouilly J., Limam, K., Béghein, C. and Allard, F. 2005. Effect of ventilation strategies on particle decay rates indoors: An experimental and modelling study. *Atmospheric Environment*, 39(27), 4885–4892.

Ferro, A.R., Kopperud, R.J. and Hildemann, L.M. 2004. Source Strengths for Indoor Human Activities that Resuspend Particulate Matter, *Environmental Science and Technology*, 38(6), 1759–1764.

Gadgil, A.J., Lobscheid, C., Abadie, M.O. and Finlayson, E.U. 2003. Indoor pollutant mixing time in an isothermal closed room: an investigation using CFD, Atmospheric Environment, Indoor Air Chemistry and Physics: Papers from Indoor Air 2002, 37, 5577–5586.

Liu, S. and Novoselac, A. 2014. Lagrangian particle modeling in the indoor environment: A comparison of RANS and LES turbulence methods (RP-1512), *HVAC&R*, 20(4), 480–495.

Mosley, R.B., Greenwell, D.J., Sparks, L.E., Guo, Z., Tucker, W.G., Fortmann, R. and Whitfield, C. 2001. Penetration of Ambient Fine Particles into the Indoor Environment, *Aerosol Science Technology*, 34(1), 127–136.

Mundt, E. 2001. Non-buoyant pollutant sources and particles in displacement ventilation, *Building and Environment*, 36(7), 829–836.

Rim, D. and Novoselac, A. 2009. Transport of particulate and gaseous pollutants in the vicinity of a human body, *Building and Environment*, 44(9), 1840–1849.

Rim, D. and Novoselac, A. (2010) Occupational Exposure to Hazardous Airborne Pollutants: Effects of Air Mixing and Source Location, *Journal of occupational and environmental hygiene*, 7(12), 683–692.

Salmanzadeh, M., Zahedi, G., Ahmadi, G., Marr, D. and Glauser, M. 2012. Computational modeling of effects of thermal plume adjacent to the body on the indoor airflow and particle transport, *Journal of Aerosol Science*, 53, 29–39.

Thatcher, T.L., Lai, A.C., Moreno-Jackson, R., Sextro, R.G. and Nazaroff, W.W. 2002. Effects of room furnishings and air speed on particle deposition rates indoors, *Atmospheric Environment*, 36(11), 1811–1819.

Zhang, T.T., Li, H. and Wang, S. 2012. Inversely tracking indoor airborne particles to locate their release sources, *Atmospheric Environment,* 55, 328–338.

Zhao, B. and Wu, J. 2009. Effect of particle spatial distribution on particle deposition in ventilation rooms, *Journal of hazardous materials,* 170(1), 449–456.