Using Multi-zone Modeling of Particle Transport to Support Building Design

Donghyun Rim
Andrew Persily
Lance Wallace
William S. Dols
Steven J. Emmerich

Engineering Laboratory, National Institute of Standards and Technology
100 Bureau Drive Gaithersburg, MD 20899

Content submitted to and published by:
2012 International Committee on Sustainable Design
Engineering and Construction Conference
November 7-12, 2012

U.S. Department of Commerce
Dr. Rebecca M. Blank, Acting Secretary

National Institute of Standards and Technology
Patrick D. Gallagher, Director

National Institute of Standards and Technology • U.S. Department of Commerce

DISCLAIMERS

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

Any link(s) to website(s) in this document have been provided because they may have information of interest to our readers. NIST does not necessarily endorse the views expressed or the facts presented on these sites. Further, NIST does not endorse any commercial products that may be advertised or available on these sites.

Using multi-zone modeling of particle transport to support building design

D. Rim[1], A.K. Persily[1], L.A. Wallace[1], W.S. Dols[1], S.J. Emmerich[1]

[1]Engineering Laboratory, National Institute of Standards and Technology, 100 Bureau Dr. MS 8633, Gaithersburg, MD 20899; PH (301) 975-4277; FAX (301) 975-4409

ABSTRACT

As building design and operation changes to meet the goals of sustainability, it is critical to address indoor air quality issues such that indoor environmental conditions are maintained. Among the indoor air contaminants of concern in this context are ultrafine particles, which have been shown to have significant health effects. Transport and fate of ultrafine particles in a building is a function of building ventilation and system operation conditions. The objective of this study is to investigate the use of a multi-zone airflow/contaminant transport model (CONTAM 3.1) for prediction of particle transport to support sustainable building design. Simulations were performed to predict outdoor particle entry into a building with different window positions, which were then compared with experimental measurements. The results indicate that indoor particle concentration varies with ventilation rate, particle penetration, and deposition loss. The results also suggest that the CONTAM model can be used in building design for prediction of particle entry into a building to investigate the impacts of various building design decisions and operating strategies.

INTRODUCTION

Indoor environmental quality is a significant goal of sustainable buildings (Persily and Emmerich 2012). Buildings and their ventilation systems should be designed to control indoor air contaminants in occupied spaces. Among many airborne contaminants in indoor environments, ultrafine particles (UFP, <100 nm in diameter) are of great interest given that they have been associated with adverse health effects such as oxidative damage to DNA (Bräuner et al., 2007) and cardiac and respiratory mortality (Stölzel et al., 2007; Oberdörster et al. 2007).

In the absence of indoor sources, UFP concentrations in buildings are determined by the entry of outdoor air particles. Especially in urban environment, penetration of outdoor UFP into buildings has a significant impact on elevated UFP levels in occupied spaces. Indoor UFP concentrations of outdoor origin vary with building and system design characteristics as well as system operation. Given the challenge of measuring indoor-outdoor UFP dynamics in buildings, modeling offers the ability to investigate design decisions and operational strategies.

The objective of this study is to investigate the ability of modeling to predict transport of particles of outdoor origin into buildings. This study develops a framework to model infiltration of ambient UFP into buildings under various building operation and weather conditions. The present study also validates the UFP transport of the multi-zone building model using full-scale experiments in a residential test building.

METHOD

Validation Experiments

Measurements were conducted in a full-scale one-level test building (see Figure 1). The test building consists of three bedrooms, two baths, kitchen, family room, and living area, having a floor area of 140 m^2 and a volume of 340 m^3. Detailed conditions for each test are summarized in Table 1.

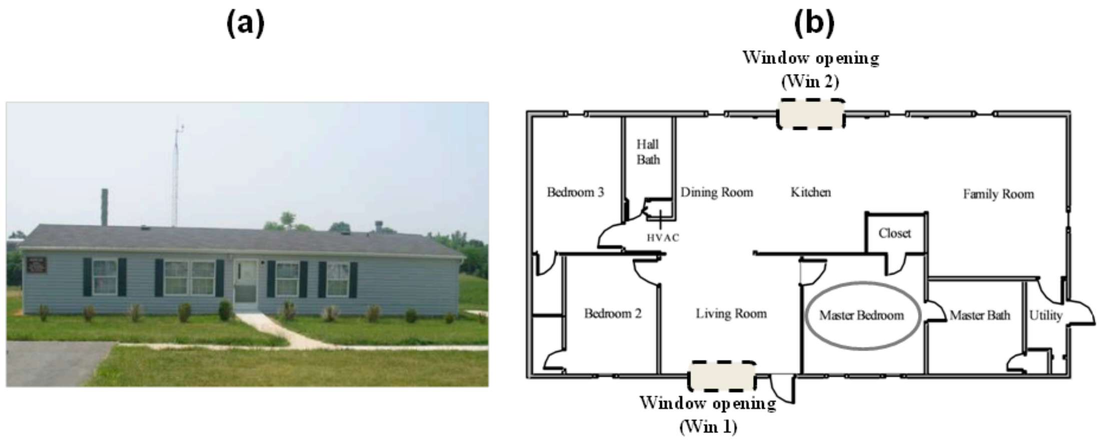

Fig. 1 a) Test building; b) Floor layout of the house.

A total of twelve 24-hour tests were conducted: four tests with all windows closed; four tests with one window (Win 1 in Figure 1) open 650 cm^2; two tests with two windows (Win 1 & Win2 in Figure 1) open 1300 cm^2 for each; and two tests with two windows (Win 1 & Win 2 in Figure 1) open 650 cm^2 each.

During the experiments, indoor and outdoor UFP ranging from 3 nm to 100 nm were monitored in the master bedroom, using Scanning Mobility Particle Sizer (SMPS). Outdoor air change rates were measured using periodic injection of a tracer gas (SF_6) in 7 rooms of the house and monitoring of SF_6 decay with an electron capture detector. A central air distribution fan, which is a part of the heating and cooling system in the building, was always on during these tests to mix the interior air at the rate of 2000 m^3/h or about 6 air changes per hour. Under closed-window condition, the tracer gas decay rates typically agree across all rooms to within 10 % RSD. When one window is open, the majority of RSDs remain within 10 %; however, when two windows are open RSDs were sometimes increased, but were still generally within 20 %.

For each experiment, three time-varying variables were monitored: air change rate (a), indoor concentration (C_{in}) and outdoor concentrations (C_{out}). The indoor concentration (C_{in}) resulting from the entry of outdoor particles can be expressed by the mass balance equation:

$$\frac{dC_{in}}{dt} = PaC_{out} - (a+k)C_{in} \qquad (1)$$

where P is the penetration coefficient (dimensionless); a is the air change rate (h^{-1}); k is the rate of UFP deposition onto interior surfaces, including ductwork and furnace filters for the building with forced air (h^{-1}), and C_{in} and C_{out} are the indoor and outdoor UFP number concentrations ($\#/cm^3$), respectively.

Using the difference form of the mass balance model (1), the estimates of penetration coefficient *(P)* and deposition loss rate (*k)* were determined based on the sum of squared errors that represents the difference between the modeled and measured indoor concentrations (Rim et al. 2010). Particle deposition onto interior surfaces, including ductwork and furnace filters is a first-order loss mechanism. The penetration coefficient (*P)* is the fraction of outdoor particles that enters a building with infiltrating air as it moves through the building envelope. The penetration coefficient (*P)* and deposition loss rate (*k)* observed with all windows closed are summarized in Table 2. The *P* and *k* values calculated for different particle sizes were used as inputs in the simulation to predict indoor concentrations.

Table 1. Test Conditions.

Window Opening	Test ID	Test Dates	Indoor conditions		Outdoor condition	
			Temp (SD) (°C)	Air Change Rate (SD) (h^{-1})	Temp (SD) (°C)	Wind Speed (m/s)
All Windows Closed	ClosedW1	3/1/09	23.6 (0.5)	0.37 (0.05)	0.43 (1.8)	6.9 (0.7)
	ClosedW2	4/25/09	22.0 (0.6)	0.20 (0.06)	22.8 (7.9)	6.2 (0.8)
	ClosedW3	5/2/09	20.3 (0.6)	0.15 (0.02)	17.2 (1.4)	6.7 (0.8)
	ClosedW4	5/9/09	20.6 (0.5)	0.19 (0.06)	23.0 (4.0)	8.0 (1.4)
One window open 8cm[a]	1WinOpn1	9/21/08	24.3 (1.0)	0.37 (0.08)	16.6 (6.3)	6.0 (0.6)
	1WinOpn2	10/4/08	22.9 (0.5)	0.33 (0.06)	15.7 (3.4)	6.1 (0.5)
	1WinOpn3	9/6/09	19.9 (1.6)	0.48 (0.12)	21.9 (3.7)	6.5 (0.9)
	1WinOpn4	9/20/09	19.4 (0.5)	0.40 (0.21)	16.5 (5.4)	6.0 (0.6)
Two windows open15cm[b]	2WinOpn1	10/2/10	21.4 (2.0)	0.88 (0.34)	14.0 (3.6)	6.4 (0.6)
	2WinOpn2	10/17/10	20.4 (2.7)	0.92 (0.40)	14.6 (6.4)	7.6 (1.5)
Two windows open 8cm[c]	2WinOpn3	7/15/11	24.5 (0.5)	0.87 (0.32)	23.1 (4.2)	6.3 (0.7)
	2WinOpn4	9/5/11	22.9 (0.5)	0.83 (0.44)	23.7 (2.8)	6.2 (0.8)

a. *one window open (Win1) 650* cm^2*;* ***b.*** *two windows open (Win1&Win2) 1300* cm^2 *each;* ***c.*** *two windows open (Win1&Win2) 650* cm^2 *each*

CONTAM Simulations

The test building described in the previous section was modeled using the CONTAM multi-zone air movement and contaminant transport program (Walton and Dols 2005). The CONTAM predictions of indoor-outdoor UFP transport were compared to the twelve measurements performed in the test building. Figure 2 shows a floor plan of the house in the CONTAM interface that shows the different zones, airflow paths (doors, wall joints, windows, *etc*.), and ductwork on the main floor of the building. The attic and crawl space were also included in the model but are not shown here. The leakage area of the individual airflow path was estimated from blower door tests of the house. This data along with ambient weather and contaminant data were used by CONTAM to calculate the airflow and indoor UFP concentrations.

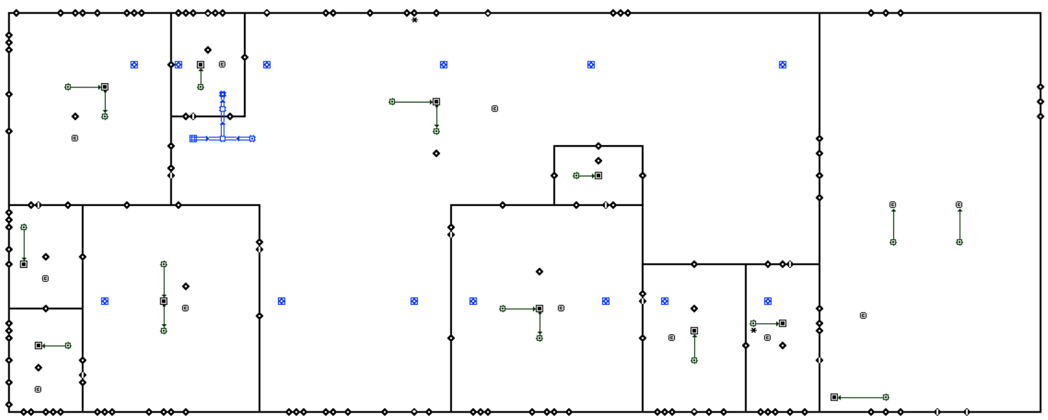

Fig. 2 CONTAM depiction of the main floor of the test building

RESULTS AND DISCUSSION

Simulation vs. Experiments

Figures 3a-3d provide indoor and outdoor UFP concentration profiles over 24 h with all windows closed (ClosedW1) in the test building, both measured and predicted with CONTAM. The CONTAM results are presented in three different ways, depending on how deposition and penetration were handled. The figures indicate that CONTAM model can predict time-varying indoor concentrations with a reasonable accuracy when both deposition and penetration are considered.

Figures 4a-4d show measurement and simulation results for a case of two windows open (2WinOpn4). The figures demonstrate that for this open window case, deposition has a larger effect than penetration in the prediction of indoor concentration. The additional consideration of penetration only minimally improves model prediction. This result implies that as a building operates with open windows, UFP entry increases and the particle filtering effect of the building shell becomes less significant compared to closed windows.

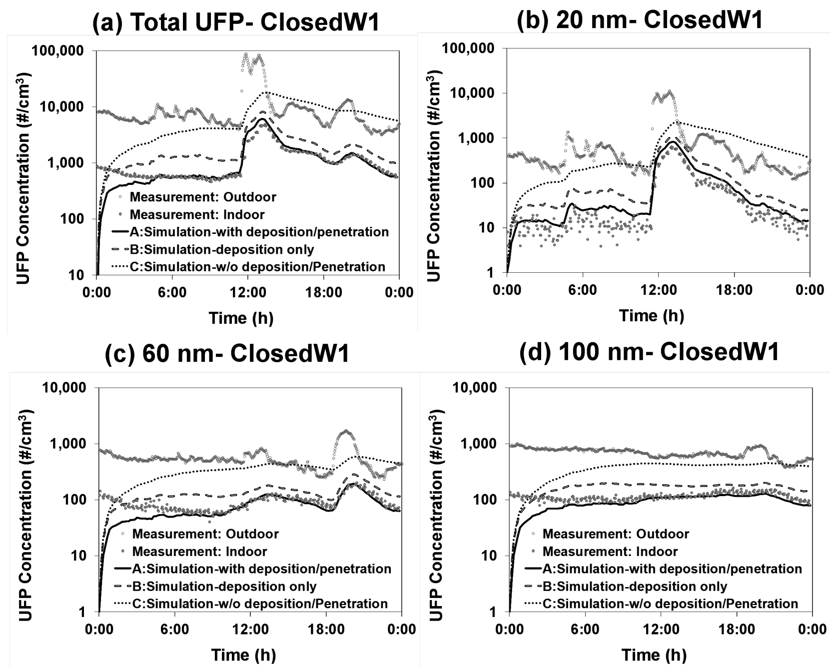

Fig 3. Time-varying particle concentration profiles – measurement vs. simulation for the test ClosedW1 for different cases of penetration and deposition: (a) Total UFP concentrations, (b) 20 nm, (c) 60 nm, and (d) 100 nm.

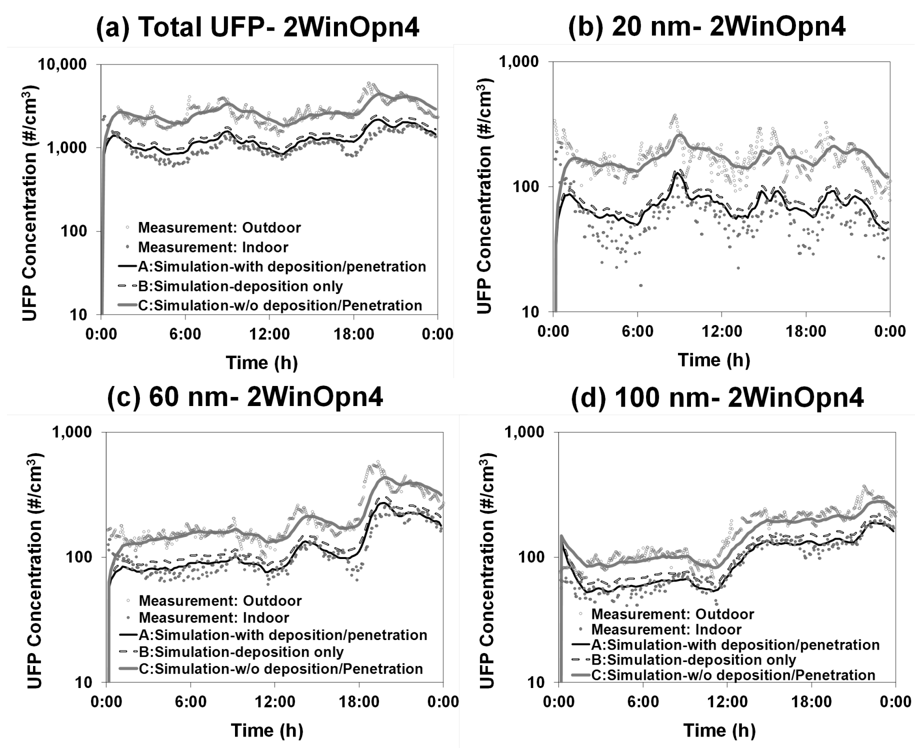

Fig 4. Time-varying (24-h) particle concentration profiles – measurement vs. simulation for the test ClosedW1: (a) Total UFP concentrations, (b) 20 nm, (c) 60 nm, and (d) 100 nm.

Figure 5 summarizes average indoor-outdoor (I-O) ratios observed and simulated for three different particle sizes (20 nm, 60 nm, and 100 nm) and total UFP (3-100 nm) under different window opening conditions. Depending on particle size, the 24-h average I-O ratio ranges from 0.09 to 0.22 for closed window, from 0.13 to 0.65 for one window open, and from 0.41 to 0.66 for two windows open. The larger I-O ratios observed with open windows suggest that more outdoor particles enter the building compared to closed windows, likely due to decreased filtering effect of the building shell. For all windows open, I-O ratio increases with particle sizes, indicating that for bigger the particles, a larger fraction of the outdoor particles infiltrate and remain airborne indoors. Comparing the measurement and simulation results of 24-h average I-O ratio, the percent differences are less than 12 % for closed windows, between 0 % and 62 % for one window open, and between 2 % and 30 % for two windows open.

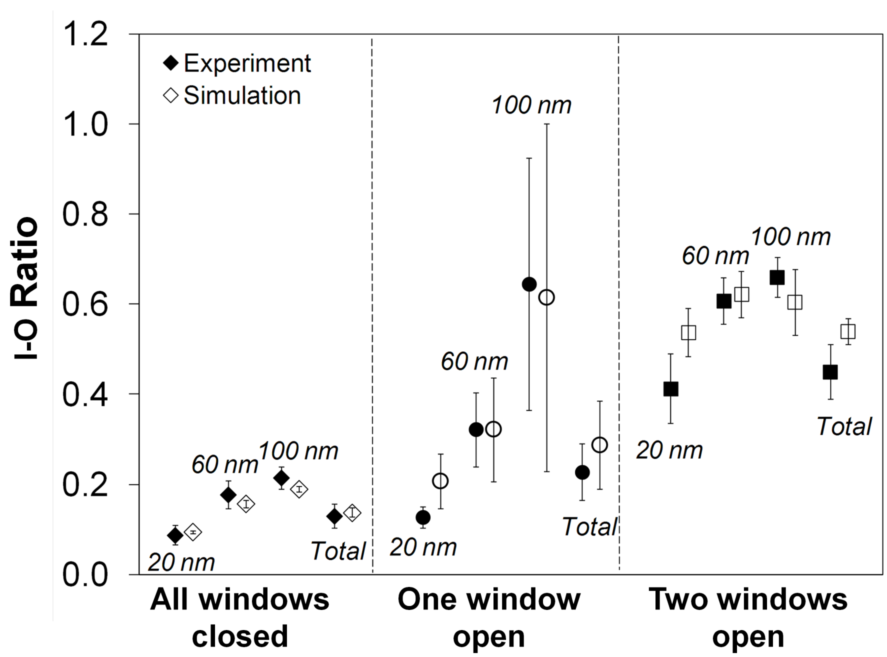

Fig 5. Indoor-outdoor (I-O) ratio for three different window operation modes: all windows closed, one window open, and two windows open. Measurement and simulation results are reported for 20 nm, 60 nm, 100 nm, and total UFP (3-100 nm). Error bars represent standard error from the mean obtained from multiple tests.

Although the simulation predicts UFP infiltration with greater accuracy for all windows closed cases, the prediction of UFP infiltration is less accurate for open window conditions and smaller particles. The larger discrepancy for the cases with open windows may be due to errors associated with the simplified airflow model that uses the mass flow power law formula to calculate airflow rate through an opening. Especially with one window opening, the simplified model might cause errors in the prediction of the inlet and outlet airflow rates within the opening. Also the model neglects the momentum effect of the wind blowing through an opening, which might increase uncertainties in the UFP transport prediction. This result indicates that accurate modeling of ventilation airflow is necessary for good predictions of airborne particle transport in a building. Nonetheless, Figure 5 shows that the simulation results can provide the general trend of particle infiltration into buildings for varied window opening conditions.

CONCLUSION

Control of airborne contaminant transport into buildings is important for the design and operation of sustainable buildings. The present study investigated the entry of outdoor ultrafine particles into a test building under three different window opening scenarios. CONTAM simulation and experimental validation were performed for a residential test building. The results show that both deposition and penetration should be considered to predict accurately the time-varying particle concentrations in buildings. With windows open, the filtering effect of the building shell decreases and more outdoor particles enter a building. The simulation predicts UFP enter with a great accuracy for all windows closed cases compared with windows open. The predictions are less accurate for open window conditions and smaller particles. The simulation results reveal that indoor particle concentration varies with ventilation rate, particle penetration, and deposition loss. However, the CONTAM model predicts the fate and transport of airborne particles with a reasonable accuracy, implying that such model can be used in early stages of building design to provide a insight into general trend of particle infiltration into buildings under various building operating scenarios.

REFERENCES

Bräuner, E.V., Forchhammer, L., et al. (2007). "Exposure to ultrafine particles from ambient air and oxidative stress-induced DNA damage. " *Environ. Health Perspect.*, 115(8):1177-1182.

Klepeis, N. E., Nelson, W. C., Ott, W. R. et al. (2001). "The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants." *J. Exposure Anal. Environ. Epidem*ol. 11: 231–252.

Oberdörster, G., Stone, V., and Donaldson, K. (2007). "Toxicology of nanoparticles: A historical perspective." *Nanotoxicology*, 1:2-25.

Persily, A.K. and Emmerich, S.J. (2012): Indoor air quality in sustainable, energy efficient buildings, HVAC&R Research, 18:1-2, 4-20.

Rim, D., Wallace, L., and Persily A. (2010). "Infiltration of outdoor ultrafine particles into a test house." *Environ. Sci. Technol.*, 44:5908–5913.

Stölzel, M., Breitner, S., et al. (2007). "Daily mortality and particulate matter in different size classes in Erfurt Germany." *J. Expo. Sci. Environ. Epidemiol.*, 17(5):458-467.

Walton, G.N. and Dols, W.S. (2005). "CONTAM 2.4 User Guide and Program Documentation" National Institute of Standards and Technology, Gaithersburg, MD.